



Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

Analysis of damage in precast concrete tunnel segments during construction phase and the influence of FRC

Treball realitzat per:
Raquel Suñé Pagès

Dirigit per:
Antonio Aguado de Cea
Javier Pablo Ainchil Lavin

Grau en:
Enginyeria Civil

Barcelona, *June 2017*

Departament d'Enginyeria Civil i Ambiental

TREBALL FINAL DE GRAU

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to Professor Antonio Aguado for his willingness to give his time so generously and to share his immense knowledge with me. My sincere thanks also goes to Javier Ainchil who gave me very useful advice and shared with me his experience in the field.

SUMMARY

The increase of the demand for tunnels is palpable. In big cities with urban density ever increasing, more and more infrastructure is competing for the limited available space, so the underground constructions have become a suitable solution. Therefore, there is a high demand for optimizing the construction processes, as well as the materials and machinery. The development of the tunnel boring machines (TBMs) had represented a significant step forward in terms of efficiency.

When constructing tunnels with TBMs, the tunnel lining is built during the excavation. The precast concrete pieces that create the lining are used as a support for the TBM hydraulic jacks to push forward the machine. This interaction between the TBM and the lining can highly influence the occurring damage in the segments. The tunnel lining is one of the most important parts of the tunnel as it ensures the protection of the cavern and the stability of the tunnel, hence the quality is of paramount importance.

As mentioned before, the construction phase of the tunnel is one of the most strenuous loading case for the segments. In the presented paper, two possible causes of segment damage are analysed: the uneven support of the segments when subjected to the hydraulic jack's loading and the radial eccentricity of the hydraulic jacks. In both cases, the stress field developed is obtained through the so-called Strut-and-tie method. This method provides a simplified version of the occurring stress fields that is very useful in the calculation of D-regions where the common flexion theory is not applicable. In addition, the simplicity of the strut-and-tie models helps to provide a physical understanding of the stress fields.

In Chapter 3 four cases of possible uneven supports of the segments are presented. Through the Strut-and-tie method, the stresses developed in the segment are analysed depending on the segment's geometrical characteristics and the load applied. In Chapter 4 the effect of the radial eccentricity of the hydraulic jacks is considered. The stress field is calculated also by means of the strut-and-tie method. In both cases, the corresponding segment damages due to the two loading situations are described.

Once the failure situations in Chapters 3 and 4 are described, the advantages of using fibres as a reinforcement for the segments are presented. Prior studies have shown that fibres have a positive influence in the behaviour of the hardened concrete and that they are suitable for the tunnel segments. Fibre reinforced concrete in tunnel segments may offer additional advantages over those of conventional reinforcement. In Chapter 5, the advantages of FRC segments and in particular to the type of failures described in the previous chapters are shown.

TABLE OF CONTENTS

1. INTRODUCTION	1
1.1 SCOPE OF THE RESEARCH	1
1.2 MOTIVATIONS.....	2
1.3 OBJECTIVES.....	3
1.4 METHODOLOGY.....	4
2. STATE OF THE ART	7
2.1 INTRODUCTION	7
2.2 PREFABRICATED CONCRETE TUNNEL SEGMENTS.....	8
2.2.1 SFRC in precast concrete tunnel segments	9
2.3 DAMAGE IN TUNNEL SEGMENTS.....	12
2.3.1 Segment damage during construction phase	15
3. STUDY OF UNEVEN SUPPORTS IN TUNNEL SEGMENTS	27
3.1 INTRODUCTION	27
3.2 CAUSES OF UNEVEN SUPPORTS.....	29
3.3 CALCULATION BASES	30
3.4 PRACTICAL CASES.....	33
3.2.1 Case 1 Vertical displacement of the support segment	33
3.2.2 Case 2 Positive turn of the support segment and negative turn of the analysed segment	40
3.2.3 Case 3 Rotation of segments “j” and “j+1”	42
3.2.4 Case 4 Rotation of segments “j” and “j+1”	46
4. RADIAL ECCENTRICITY OF THE HYDRAULIC JACKS	49
4.1 INTRODUCTION	49
4.2 STRESS DEVELOPMENT AND CRACK PATTERNS.....	51
4.3 SOLID BLOCK MEMBER UNDER CONCENTRATED LOAD.....	54
4.4 EFFECT OF RADIAL ECCENTRICITY “ ϵ_r ”	55
5. STEEL FIBRES IN PRECAST CONCRETE SEGMENTS	59
5.1 INTRODUCTION	59
5.2 MECHANICAL PROPERTIES OF SFRC.....	64
5.2.1 Influence of the orientation of the fibres.....	67
5.3 CONSTITUTIVE MODELS FOR THE DESIGN OF SFRC MEMBERS ACCORDING TO THE EHE-08.....	68
5.4 PRACTICAL CASE	68
5.4.1 Uneven supports	69

5.4.2 Solid block member under concentrated load	72
5.4.3 Radial eccentricity	73
6. CONCLUSIONS	77
6.1 GENERAL CONCLUSIONS.....	77
6.2 SPECIFIC CONCLUSIONS.....	78
6.3 FUTURE PERSPECTIVES	81
REFERENCES.....	83

LIST OF FIGURES

Figure 1.1 Number of kilometres excavated by means of TBMs	2
Figure 1.2 Scheme of the subjects of the paper	4
Figure 2.1 Schematic single shield TBM	8
Figure 2.2 Tunnel segment	9
Figure 2.3 Types of fibers geometries	10
Figure 2.4 Influence of the amount of steel fibres on the ultimate load and on the maximum crack width	11
Figure 2.5 Effect of casting and compacting on the fibre orientation	11
Figure 2.6 Loading stages of the tunnel segments	12
Figure 2.7 Forces acting on demoulding load case (a), Forces acting on the bottom segment during storage load case (b)	13
Figure 2.8 Demoulding with vacuum lifter (a), segment storage (b), Segment transportation	14
Figure 2.9 Construction phase damage causes	15
Figure 2.10 Frequency of segment damage during construction	17
Figure 2.11 Thrust jacks (a), Schematic stress distribution (b)	19
Figure 2.12 Development of splitting stresses under the load	20
Figure 2.13 Grout injection through tail skin	21
Figure 2.14 Back grouting pressure	22
Figure 2.15 Dowel and socket connection tolerances	23
Figure 2.16 Criteria for position of the key segment	25
Figure 2.17 Trumpet shape	26
Figure 3.1 Perfect configuration of the segments	28
Figure 3.2 Cases of uneven supports of the segments	28
Figure 3.3 Accumulation of irregularities among adjoining rings	30
Figure 3.4 Strut-and-tie model for a deep beam	31
Figure 3.5 Ideal configuration for both cases, with and without “i + 1” segment.	32
Figure 3.6 Tunnel segment geometry example	32
Figure 3.7 Hydraulic jacks’ configuration	33
Figure 3.8 Strut-and-tie scheme case 1	34
Figure 3.9 Geometry of the segment, equilibrium equations and compatibility equation	34
Figure 3.10 Range of eccentricity “x”	36
Figure 3.11 Tension-eccentricity diagram for the 6 particular cases	36

Figure 3.12 Relation between slope “m” and segment’s width “H”	38
Figure 3.13 Relation between segment’s length “L” and parameter “A”	38
Figure 3.14 Relation between the parameter “A” and ratio “L/H”	39
Figure 3.15 Segment damage	40
Figure 3.16 Main stress fields according to different support conditions.	40
Figure 3.17 Geometric parameters of segment “i” and values of the vertical reactions.	41
Figure 3.18 Punctual failure in the lateral and middle supports of the segment.	42
Figure 3.19 Strut-and-tie model for case 3	42
Figure 3.20 Geometry of segment “i” and bending moment’s diagram with equilibrium equations, maximal bending moment and compatibility equation	43
Figure 3.21 Relation between “ L/H “ ratio and the tensile stress T_1	45
Figure 3.22 Segment damage case 3	46
Figure 3.23 Strut-and-tie models for case 4	46
Figure 3.24 Segment “i” geometry, equilibrium equations and compatibility equation	47
Figure 3.25 Segment damage case 4	48
Figure 4.1 Shoe's geometry of a pair of hydraulic jacks supported in a segment	50
Figure 4.2 Radial eccentricity “e”	50
Figure 4.3 Radial eccentricity of hydraulic jacks in the L9 metro line in Barcelona	50
Figure 4.4 Representation of the stress field in a transversal cut of the segment through a strut-and-tie model (a). Variation of the stresses along the segment depth without eccentricity (b). Stress field regarding radial eccentricity “ ϵ_r ” (c)	51
Figure 4.5 Strut-and-tie model for the area under the bearing pads (a). Typical conic shaped fracture in a compression test. (b)	53
Figure 4.6 Strut-and-tie model for a specimen in a diametral compression test (a). Diametral compression of a cylindric specimen (b). Distribution of horizontal stresses (c).....	54
Figure 4.7 Longitudinal crack in the segment due to a concentrated load and compressive strength test	54
Figure 4.8 Effect of radial eccentricity in the stres field of the segment	55
Figure 4.9 Fracture of an edge’s piece and indirect tensile stress test specimen crack pattern. Geometry of the fractured piece	56
Figure 4.10 Sketch of the fractured piece and its geometry parameters	56
Figure 5.1 Type of fibres according to the EHE-08	60
Figure 5.2 Stress-strain relationship of three types of concrete	62
Figure 5.3 Behaviour of conventional reinforced concrete and fibres reinforced concrete under tensile stresses and comparison of ductility	62

Figure 5.4 Effect of temperature on compressive strength of SFRC (a). Effect of temperature on tensile strength of SFRC (b)63

Figure 5.5 Tunnel segment reinforcement construction (a). Reinforcement storage area (b) ...64

Figure 5.6 Tensile stress behaviour of FRC65

Figure 5.7 Typical load-crack opening diagram67

Figure 5.8 Wall-effect with different boundary conditions67

Figure 5.9. Solid block member under concentrated load with a Strut-and-tie model of the stress field72

LIST OF TABLES

Table 1.1 Subjects of the paper and the corresponding objectives	3
Table 2.1 Most common segment damages in tunnel segments	17
Table 2.2 Segment's damage causes	18
Table 3.1 Scheme of the 4 analysed cases	29
Table 3.2 Real tunnels data	35
Table 3.3 Geometric parameters of the segments and parameters of the function $T_1(x)$	37
Table 3.4 Existing tunnels data	44
Table 5.1 Advantages of FRC	61
Table 5.2 Main test methods for the characterization of the post cracking behaviour of FRC...	66
Table 5.3 Constitutive models considered in EHE-08	68
Table 5.4 Data of Font Santa-Trinitat tunnel	69
Table 5.5 Characteristics of the Steel fibres, Steel and Concrete	69
Table 5.6 Uneven support cases	70

SYMBOLS

α	Angle of the fractured piece
β	Angle between a strut and a tie
γ_s	Factor of safety of steel
δ	Vertical displacement
ε	Strain
ε_c	Strain of concrete
ε_s	Strain of steel
ε_r	Radial eccentricity of the hydraulic jack
ε_u	Ultimate strain of concrete
θ	Angle, rotation angle
λ_f	Slenderness of the fibres
σ	Stress
σ_1	Tensile stress in a trilinear $[\sigma-\varepsilon]$ diagram
σ_3	Stress defining the third point of a trilinear $[\sigma-\varepsilon]$ diagram
τ_c	Shear resistance of concrete
\emptyset	Diameter of the tunnel, diameter of the steel rebar
a_1	Width of the hydraulic jack shoe
f_c	Compressive strength of concrete
f_{ck}	Characteristic compressive strength of concrete
f_{ct}	Tensile strength of concrete
$f_{ct,fl}$	Flexural tensile strength of concrete
$f_{ctR,d}$	Design residual tensile strength of concrete
$f_{ctR1,d}$	Design residual tensile strength of concrete associated to a crack opening of 0,5 mm
$f_{ctR3,d}$	Design residual tensile strength of concrete associated to a crack opening of 2,5 mm
$f_{R,1,k}$	Characteristic residual strength of concrete associated to a crack opening of 0,5 mm
$f_{R,3,k}$	Characteristic residual strength of concrete associated to a crack opening of 2,5 mm
f_R	Residual flexural strength of concrete
F_L	Limit of proportionality of concrete
F_1	Stress associated to a crack opening of 0,5 mm
F_3	Stress associated to a crack opening of 2,5 mm
f_{yk}	Yield strength of steel
f_{yd}	Design yield strength of steel

Δ_s	Area of passive reinforcement
Δ_c	Tensioned area of concrete
C	Compression strut
T	Tension tie
d_f	Equivalent diameter of fibres
l_f	Length of the fibres
V_f	Volume fraction of fibres
e	Edge of the tunnel segment
H	Width of the tunnel segment
L	Length of the tunnel segment
M_{max}	Maximal bending moment
N_d	External loading according to EHE-08
P	Load
w	Crack width (opening)
x	Eccentricity of the support segment

1. INTRODUCTION

1.1 SCOPE OF THE RESEARCH

Tunnels are one of the oldest big civil works of human history. In the Iberian Peninsula, the Romans and the Muslims were responsible for the execution of the greatest underground constructions in the region. The first tunnels were built to provide the population with water and for mining purposes. In the Middle Ages, the construction of tunnels was mainly due to defensive purposes. It was with the advent of the industrial revolution that the railways were invented in the nineteenth century and the need to cut through mountainous areas arose. From then on, the number of tunnels that have been constructed are countless as well as their technical improvements.

Today, a great efficiency has been achieved thanks to the development of Tunnel boring machines (TBM) which are able to excavate long distances through different kinds of soil conditions. One of the main advantages of TBMs is that they can excavate limiting the disturbance to the surrounding ground. Therefore, it is suitable to use TBMs to excavate in heavily urbanized areas. For instance, the excavation of metro tunnels. In Figure 1.1 the number of kilometres constructed by means of TBM in the metro lines of Madrid, Barcelona, Valencia and Sevilla are shown.

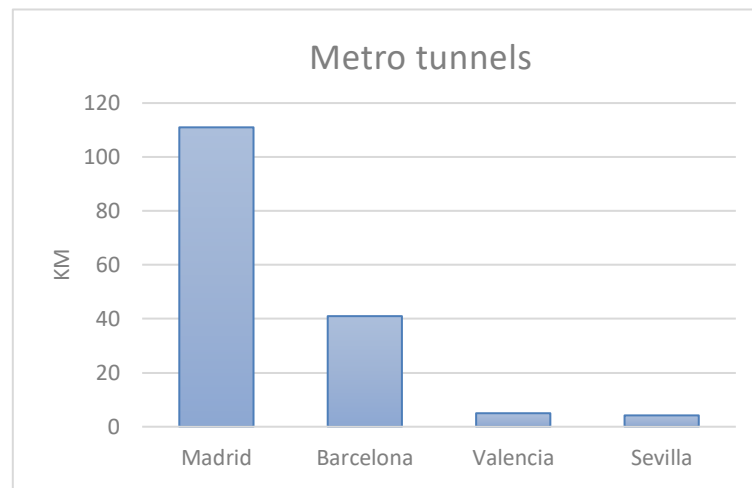


Figure 1.1 Number of kilometres excavated by means of TBMs (<http://obrasurbanas.es/images/pdf/tuneladoras.pdf>)

The demand for longer tunnels with bigger diameters is continuously increasing, however, the research in the field is not keeping up. The lack of knowledge in some of the aspects concerning tunnel construction may lead to the design of new tunnels based in previous experience. Nevertheless, the boundary conditions of every project are different and some unexpected structural or durability problems in the tunnel lining might arise (Cavalaro 2009). That is why, it is of great importance to study the behaviour of the lining when exposed to external effects. According to research, one of the main damaging stages for the segments of the tunnel lining is the construction stage.

For instance, during the construction phase the interaction between the TBM and the lining must be carefully considered. The connection point between the TBM and the segments are the hydraulic jacks. The hydraulic jacks support themselves on the previously installed ring to push forward the shield and continue the excavation. The pushing pressure of the hydraulic jacks on the segments while excavating may lead to different types of failure. In addition, the behaviour of the joints between segments may lead to uneven supports for the next installed rings what can significantly increase the damage while being pushed by the hydraulic jacks.

Research in new materials for the reinforcement of the segments is also a suitable way to improve the quality of the tunnel lining. Since over 20 years, the introduction of fibres in the tunnel segments is being investigated. It is proven that the fibres can have a positive impact on the lining, both in structural and durability aspects. However, the structural contribution of fibres in existing tunnels has not been considered in the design. It is possibly due to the lack of design recommendations for fibre reinforced concrete members.

1.2 MOTIVATIONS

In several cases, it has been proven that the main damages in the tunnel segments occur during the construction phase. Problems such as cracks and leakage will lead to inferior quality of the tunnel lining. Therefore, the optimization of the segments and the construction processes are the main concerns among companies and researchers.

A good understanding of the behaviour of the tunnel lining and the most common types of damages as well as their causes are of great importance for the design of tunnels with a better quality and for more efficient construction processes.

Nevertheless, in most of the real projects, the design of the tunnel lining is carried out with some basic assumptions that may not match with the real situation. It is considered in the design that the support conditions of the segments when they are loaded by the hydraulic jacks is perfect or that the radial eccentricity of the hydraulic jacks does not exceed a certain value. In practice, there is clear evidence that these assumptions lead to damage in the segments. Therefore, the analysis of these situations can be very helpful to reduce the occurring segment's damages.

It is worth noting that the incorporation of reinforcement alternatives such as fibres in the concrete can be advantageous both in structural and durability aspects. Therefore, the interest in the research of the fibre reinforced concrete elements, in particular, the tunnel segments has increased in the recent years.

1.3 OBJECTIVES

As mentioned above, the appearance of cracks and different types of failure in the segments is a real concern in many tunnel constructions. This paper aims to provide a more detailed analysis of two possible damage causes: the uneven supports of the segments while being pushed by the hydraulic jacks and the radial eccentricity of the hydraulic jacks when applying the pushing pressure in the segment. As a second objective, an overview of the advantages of using fibre reinforced concrete regarding the failure cases exposed above is shown.

Table 1.1 Subjects of the paper and the corresponding objectives.

Subject	Specific Objectives
Uneven supports of the segments	<ul style="list-style-type: none"> Identify the main cases of uneven supports that occur during construction phase. Obtain equations for the values of the main stresses developed in the segment in every uneven support case when possible. Study the values of the main tensile stress fields in every case by means of segment geometry characteristics of real tunnel examples.
Radial eccentricity of the hydraulic jacks	<ul style="list-style-type: none"> Identify the main types of failure due to the radial eccentricity of the hydraulic jacks. Assimilate the segment's failure patterns to existing tests. Obtain equations for the values of the main stresses developed in the segment.
Introduction of fibres in the design of the segments' reinforcement	<ul style="list-style-type: none"> Identify the mechanical and durability properties of the SFRC. Introduction to the design of SFRC members according to the EHE-08. Proposal of theoretical design of segment's reinforcement, with conventional rebar and steel fibres. Identify the advantages of SFRC in the segments according to the failure cases analysed in the project.

1.4 METHODOLOGY

According to the research carried out in the state of the art in Chapter 2, some of the main concerns regarding segment failure are considered in this study. The paper is divided into three main chapters as shown in Figure 1.2: analysis of the uneven support conditions of the segments (Chapter 3), analysis of radial eccentricity of the hydraulic jacks (Chapter 4) and influence of fibres (Chapter 5).

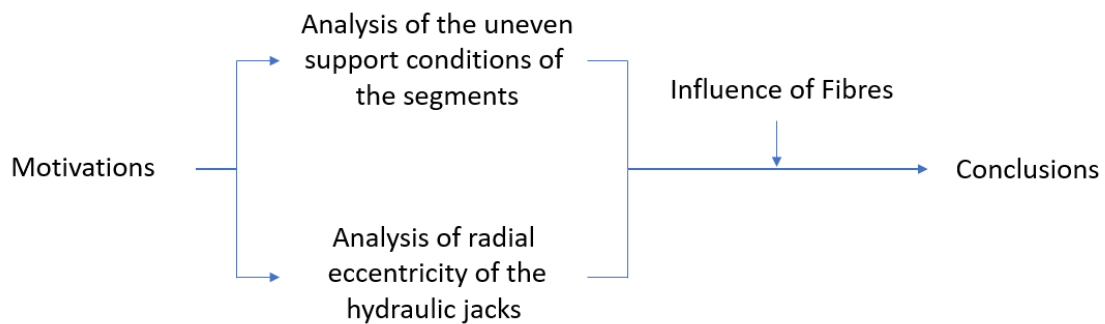


Figure 1.2 Scheme of the subjects of the paper

In Chapter 3, the stresses developed in a segment due to the pressure of the hydraulic jacks and the influence of the uneven support on them have been analysed. First of all, four cases of possible wrong positions of the segments that can lead to uneven supports for the next rings have been identified.

For the analysis, some assumptions have been done in order to simplify the further calculations: the segment is considered as a deep beam, the longitudinal joints of the segment are straight and the pushing pressure is transferred through two hydraulic jacks per segment.

There are two critical moments when the segments are loaded by the hydraulic jacks. One is when the TBM presses the segments to move forward and the second is when the TBM is simply keeping the segments in place while the rest of the ring is constructed. Therefore, every case is analysed separately in order to determine the worst scenario of the developed stresses.

The analysis of the stresses is carried out by means of the so-called Strut-and-tie method which provides a simplified analysis of regions where the common flexion theory is not applicable. As concrete works well under compression stresses, the cases where the main stress field corresponds to a compression stress field is not calculated. The interesting thing is to identify the cases which lead to the development of high tensile stresses. For every case, a strut-and-tie model is proposed and an equation for the main tensile stresses is obtained. This equation depends on the value of the pushing pressure and the geometric characteristics of the segment.

By means of real values of the segment's geometry from existing tunnels, a comparison between the values of the tensile stresses developed in every tunnel is done. The aim is to obtain any relevant correlation between the tensile stresses developed and the geometrical parameters.

In Chapter 4, another possible cause of segment damage is analysed. As previously mentioned, the eccentricity of the hydraulic jacks when applying the pushing pressure can lead to failures in the segments. For the analysis, a transversal cut in the segment right in the middle of the hydraulic jack's shoe is done. This transversal cut is considered in the calculations as a solid block member under a concentrated load and the stress fields are represented through a strut-and-tie model. To acquire a better understanding of the type of failure that may occur, the failure patterns of the segment are associated to the ones in a compressive strength test and in an indirect tensile stress test.

First, the effect of the pushing pressure without eccentricity is shown and the corresponding type of failure analysed according to the Spanish regulation EHE-08. Subsequently, the effect of the radial eccentricity is presented which may lead to a different kind of failure. Both cases are carefully analysed and the main stresses calculated.

The aim of Chapter 5 is to provide an overview of the advantages of introducing fibres in the tunnel segments. First, the mechanical and durability properties of the fibre reinforced concrete are presented and subsequently the constitutive models used in the design of FRC members according to the Spanish regulation EHE-08 are presented. Once the behaviour of the fibres in the concrete is known, the effect of them in the optimization of the reinforcement according to the damages presented in Chapter 3 and 4 is described.

2. STATE OF THE ART

2.1 INTRODUCTION

A tunnel boring machine (TBM) is designed to carry out an excavation of a full cavern by means of a rotatory cutterhead. At the same time, it is able to install prefabricated concrete segments as structural support for the tunnel.

The tunnelling machine is composed by a rotatory cutterhead, equipped with disc cutters which excavate the tunnel face. The excavated material is removed from the front and brought outside the tunnel by means of a conveyor belt or buckets. An important part of the tunnelling machine is the shield, in some cases there can be two, which protect the excavation and segment installation equipment from the outside geological conditions and prevent the penetration of water in the working area.

The advance of the machine is carried out by means of hydraulic thrust cylinders which push the shield forward by supporting themselves on the previously installed ring or on the so-called grippers with auxiliary thrust cylinders in case of double shield machines.

Simultaneously to excavating, segments are assembled in the tailskin section of the shield (last part of the shield). The assembly procedure consists on building a ring with the segments by means of an erector that elevates and situates them in the corresponding place. As

there is a gap between the cylinder composed by the sequence of built rings and the ground, it is filled with grouting material.

Excavation by means of tunnel boring machines has become one of the most widely used excavating methods. It is not only due to its high performance but also because of its versatility. A TBM can excavate in a wide range of depths, dimensions and ground conditions. The increased usage of tunnel boring machines (TBM) requires a search for constant improvement in the field and therefore it has become a topic of great interest in civil engineering. In Figure 2.1 a scheme of a TBM is shown.

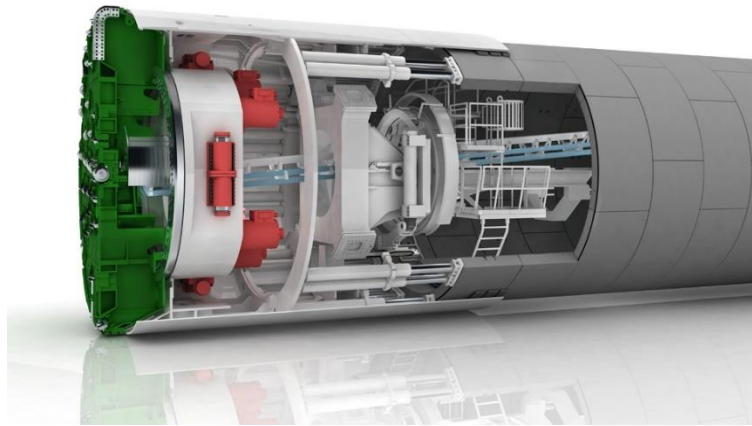


Figure 2.1 Schematic single shield TBM
(<https://www.herrenknecht.com/en/products/core-products/tunnelling/single-shield-tbm.html>)

One of the main concerns about excavation by means of tunnel boring machines is the behaviour of the tunnel linings. It is observed in many construction sites that sometimes the performance of the segments is not as expected and crack patterns are developed. Failure in the segments can occur due to several reasons and can cause high maintenance costs during their serviceable life.

This chapter gives the state of the art of tunnel linings used in the construction of tunnels through TBM machines. According to the experience in the field and research done so far, the main type of segment failures and their causes are described below. In addition, an introduction to fibre reinforced concrete (FRC) as a suitable material for tunnel linings is exposed according to recent research.

2.2 PREFABRICATED CONCRETE TUNNEL SEGMENTS

The stability of the inner walls of a tunnel excavated through TBM machines is given by the so-called tunnel segments. The segments are pieces made of generally reinforced concrete that are placed forming a ring. The sequence of the rings forms a cylinder, which gives the structural support of the tunnel and at the same time prevents the penetration of liquids inside the cavern.

In Figure 2.2 the sketch of a segment is shown together with some of its relevant elements, the gaskets, the packers and the two different kinds of joints. Segments are placed in

a way that form two kinds of joints: longitudinal joints, which are in the same direction as the tunnel axis and circumferential joints, which are the joints between embedded rings in an orthogonal direction to the tunnel axis. The importance of the joints in the tunnel structure will be considered further in a following section. However, it is important to mention that joints are critical areas in the cylinder structure in terms of possible development of stresses and leakage.

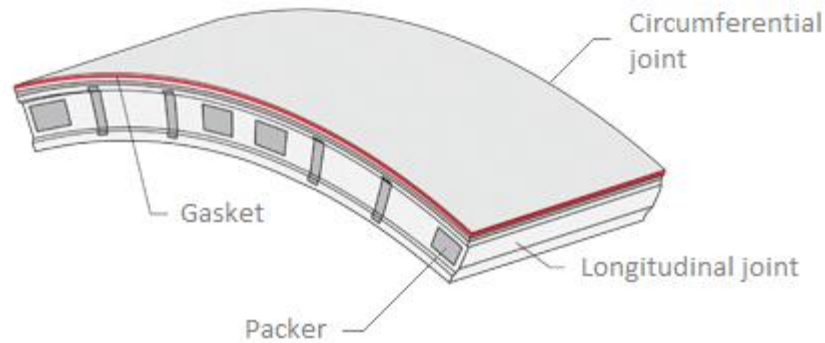


Figure 2.2 Tunnel segment
(<http://segment-tracker.tunnelsoft.com/prepare-for-tunnel>)

In order to provide the sealing of the tunnel lining, rubber gaskets or packers are used. Packers have an important structural role in the tunnel lining, as they ensure the connection between circumferential and longitudinal joints. Packers are usually accompanied by other locking elements such as bolts or dowel and socket connections. In case of bolts, they can be removed later.

Packers are also responsible for uniformly distributing the loads in the contact surface between segments, avoiding high stress concentrations, load eccentricity and tangential stresses (Cavalaro 2009). The packers are also important when the jack forces are applied in order to push forward the shield.

Traditionally, segments were made of reinforced concrete. In order to improve the quality of the segments, new materials such as different type of fibres as reinforcement were investigated. In the following section, an introduction to fibres and their advantages over conventional reinforcement is done. Mainly, for structural purposes the most widely used type of fibres are the steel fibres.

2.2.1 SFRC in precast concrete tunnel segments

Recently, fibres have been introduced in the segment manufacturing as they are advantageous in both structural performance and in cost reduction (Caratelli, et al. 2010).

Tunnel segments are generally made of conventional reinforced concrete. However, a great interest for SFRC is growing among designers and producers due to the enhanced toughness introduced by such materials (Blom 2002, Burgers et al. 2007). This toughness allows a partial or even total substitution of the conventional reinforcement. In case of tunnel segments, fibres can be advantageous as the bending shape of the segments leads to the use of ordinary reinforcement with complex detailing (Carartelli 2010).

In construction, fibres of different shapes and sizes made of steel, synthetics, glass or natural materials can be used (Löfgren 2005). However, in terms of structural and durability purposes in tunnel segments, steel fibres are the most widely used.

The steel fibres commonly used have a round cross-section, a diameter varying from 0.2 to 1 mm and a length ranging from 10 to 60 mm (Löfgren 2005). However, it must be considered when choosing the kind of fibre that its length can be a critical factor, as they must be long enough to be well embedded in the concrete-fibre matrix but not too much to reduce the paste workability. The lack of workability can result in a stiffer mixture and sometimes fibre balling.

Fibres are often characterized by the aspect ratio which is the ratio between the fibre length and the fibre diameter (Kooiman 2000). In terms of providing a good anchorage with the matrix, fibres often have some sort of deformation on its ends. In Figure 2.3 different kinds of fibres geometries are shown. The shape of the fibres may be very varied: straight, undulated, corrugated, shaped with different-shaped ends, etc (EHE-08 2008).

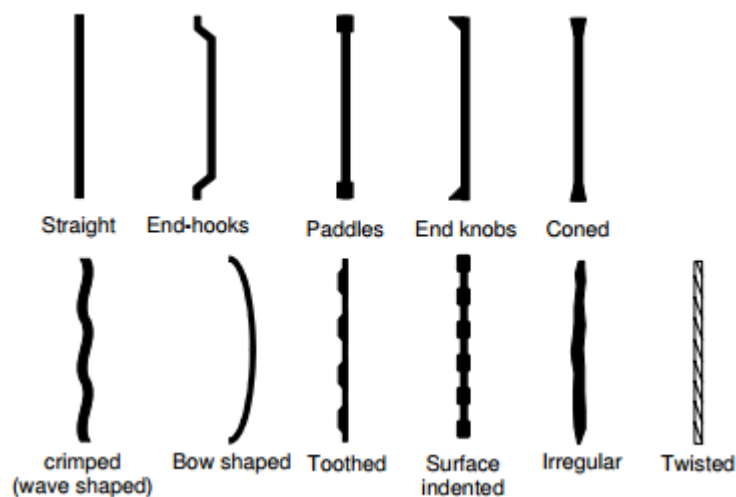


Figure 2.3 Types of fibers geometries (Löfgren 2005)

In the following section, the structural and durability performance of the SFRC are discussed considering recent research.

Structural and durability performance of SFRC

Fibres are randomly distributed through the concrete matrix, this provides a better crack control and the ability to hold the concrete matrix together. It is proven that the introduction of fibres in concrete can improve its chipping and spalling behaviour under extreme loading, even after the formation of successive cracks. Since the fibre reinforcement is also present in the cover zone, the impact and fatigue resistance is increased. (Plizzari and Tiberti 2007, Meng et al. 2016). An example of extreme loading in the segments could be the thrust force introduced by the hydraulic jacks of the TBM during the installation process.

In terms of structural aspects, the fibre reinforcement improves the performance of concrete under tensile actions, remarkably increasing the toughness and enhancing the cracking control. (Caratelli et al. 2010). According to Burgers et al. (2007), the toughness gained thanks

to the introduction of steel fibres involves an ability to resist stresses after cracking and allows favourable stress distribution which results in smaller crack width. A bridging effect is produced between cracks due to fibres that significantly reduces the crack width (Buratti et al. 2013).

As can be seen in Figure 2.4 from a study carried out by Burgers et al. (2007) for the metro line in Barcelona, the amount of steel fibres remarkably influences in the reduction of crack width.

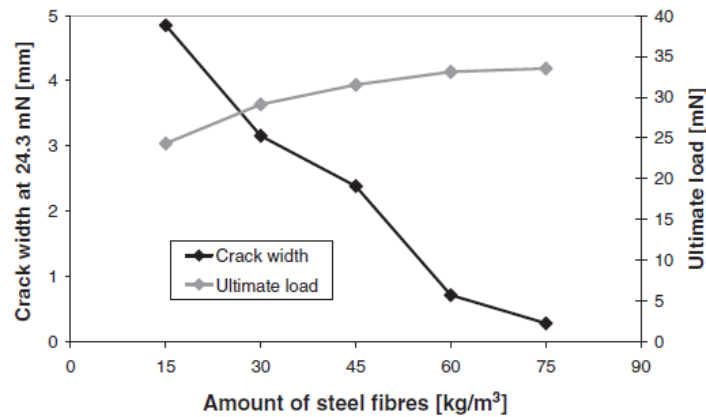


Figure 2.4 Influence of the amount of steel fibres on the ultimate load and on the maximum crack width. (Burgers et al. 2007)

In terms of durability aspects, the introduction of fibres can improve the properties of concrete gaining a bigger corrosion and fire resistance (kasper et al. 2007) since fibres can partially or completely substitute the most vulnerable parts, namely the reinforcing steel cages (Meng et al. 2016).

According to Kooiman (2000), an important factor that can influence on the fibre efficiency in tunnel segments is the orientation of the fibres throughout the segment. By means of casting tests and tensile splitting tests carried out by Kooiman and Plizzari respectively, the results showed that the quality of the composite material varies over the segment’s thickness. This inhomogeneity throughout the segment can be explained due to the compaction and vibration process when bleeding can occur. The effects on the orientation of the fibres due to the casting and compaction process are shown in Figure 2.5.

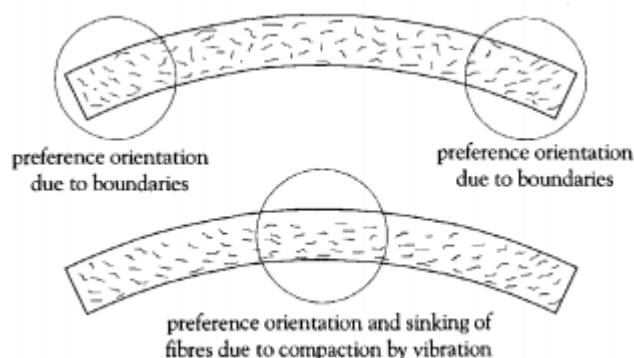


Figure 2.5 Effect of casting and compacting on the fibre orientation. (Kooiman 2000)

As can be seen in Figure 2.5 the matrix is stronger at the mould side than at the casting surface. Because of this inhomogeneous orientation, the mechanical properties of the segment will not be the same in every direction (Kooiman 2000, Plizzari 2009).

Despite the fact that an in-depth research on SFRC for tunnel segments has been carried out, it must be underlined that there is a lack of special design rules for it. Engineers have usually designed SFRC segments by adopting the design rules for conventional reinforced concrete or the national codes concerning FRC structures (Sorelli and Toutlemonde 2013). However, in the latest update of the Spanish regulation for concrete (EHE-08 2008), an annex for SFRC design rules was introduced.

In terms of optimizing the performance of the segments for instance in the case of this paper with SFRC, first it is important to have an expansive understanding of the damage occurred in tunnel segments and their corresponding causes. In the following section, these issues are described according to the bibliography so far.

2.3 DAMAGE IN TUNNEL SEGMENTS

Tunnel segments are one of the most important elements in a tunnel construction with TBM machines. Therefore, their performance during all the stages must be as optimal as possible. Segments have an important role on the tunnel, not only in terms of structural stability but also of impermeability.

This chapter starts with an overview of every loading stage that a segment is exposed to. According to the ACI Committee 544 (2014), the loading stages are grouped into four: manufacturing, transportation, installation and serviceable life. Every stage may influence in the developing of internal stresses, which later can be of great importance in terms of crack formation. Figure 2.6 shows the sequence of loading stages of the segments.



Figure 2.6 Loading stages of the tunnel segments

Hereafter, a deeper research on the installation stage or construction phase is presented as this project is focused only on the possible punctual and structural failure of segments during this phase. The project starts with the identification of the most common types of failure in a segment and concludes with a detailed explanation of the possible damage causes.

Segment failure is difficult to control, as the segments can be damaged due to several reasons in every stage of their serviceable life. To ensure the best performance of a segment and avoid as much as possible any kind of failure, every stage of segment loading must be considered.

As follows, the main loading stages used for segment design with SFRC are described according to the ACI Committee 544 (2014).

Segment manufacturing

Segment manufacturing goes from the stage of design, including the selection of materials, to the demoulding and storage state. The selection of materials is not only important in terms of avoiding failure or retarding it, but also in terms of crack development after failure (ACI 544 Committee 2014).

The two main types of reinforcement are conventional rebar and steel fibres. Since recently, the reinforcement of the segments was only carried out by conventional rebar, however the introduction of steel fibres reinforcement is increasingly common as they bring several advantages both in terms of structural behaviour and durability.

In the manufacturing procedure, concrete is poured into moulds, where the concrete sets and hardens. After curing, segments must be extracted from its mould. To do so, there are two possible methods, vacuum lifting or mechanical lifting.

In case of vacuum lifting, the segment is lifted through suction and tensions can occur due to bending moments induced by its own dead weight. This mechanism can be modelled with two cantilever beams, each one being half of a segment long and with two moment resisting connections. As the load during demoulding procedure can be considered as a dynamic effect, it is commonly calculated through multiplying the static effect per a value of 1,4.

In case of mechanic lifting devices, for example bolts, it must be considered the possible failure of the connection. These connections can break by three possible ways, through the concrete interface, through the steel bolt or through the so-called truncated cone shape failure of the concrete.

In order to gain the 28-day strength, segments are placed in a stacked yard before being taken to the construction site. They are usually grouped by rings, in other words, if every tunnel ring is formed by 6 segments and the key, these segments will be piled up together.

As a support on the floor and between the segments, wood blockings are used. Two important parameters that are of great influence in the loading case of storage are, the distance between the two supports and the distance between the support and the edge of the segment. These distances must minimize the bending moments occurred due to the own weight of the segments. An unfavourable situation is when the supports of the segments above have an eccentricity in relation to the segments on the bottom, therefore, an extra bending moment due to the accumulated weight occurs. In Figure 2.7 forces acting on the segment piece are illustrated, the distributed load represents the own dead weight of the segments.

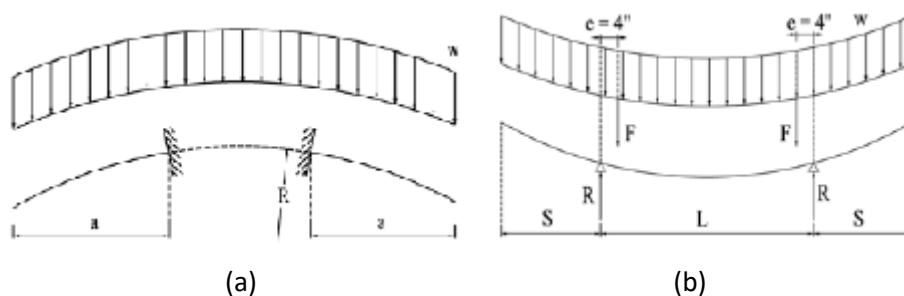


Figure 2.7 Forces acting on demoulding load case (a), Forces acting on the bottom segment during storage load case (b). (ACI 544 Committee 2014)

Transportation and handling

The segments are transported from the plant to the construction site by trucks. On the other hand, when segments are transported through the tunnel until the front of the TBM, it is done by means of rails. The loading situation is similar to the one of storage, wood supports are provided and the eccentricity of the them must be carefully controlled.

Similar vacuum lifting devices as in the demoulding procedure are used to handle the segments during construction stage. Therefore, the loading case is the same as in the demoulding procedure, however, an extra dynamic effect must be considered. Figure 2.8 shows three of the possible loading stages.

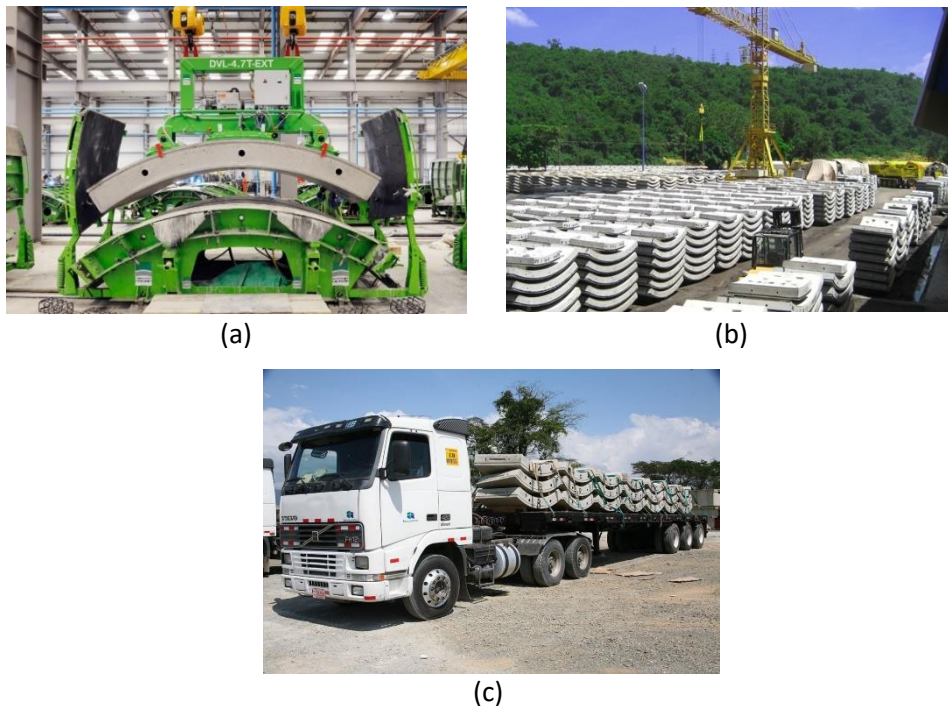


Figure 2.8 Demoulding with vacuum lifter (a), Segment storage (b), Segment transportation (c)
<http://euroconcretos.com/productos/revestimiento-de-tuneles/>
<http://www.herrenknecht-formwork.com/es/medias/descargas.html>

Installation or construction stage

The loading cases considered in the design of the segments during the construction phase, consist of the following phases: the erection of the segment, its placement, the thrust of the hydraulic jacks against them in order to push forward the shield and the filling of the gap between the cylinder and the ground.

This particular stage is described more carefully in the next section as it is of great importance for the developing of the work carried out in this project. However, it must be underlined that the main failure causes during this phase are the action of the thrust jacks and the pressure induced by the grout injection in the annular space. As a result, the main occurring effects in this phase are both bending moments and axial forces.

Serviceability stage

The loading cases during service conditions are defined by the interaction between the tunnel lining and the ground and possible external effects like surcharge or special loads. In the interaction between the ground and the lining, the ground and porewater pressure are the main parameters that must be considered. In addition to the internal forces and stresses due to the force transfer at longitudinal joints and surcharge loads like traffic or buildings.

The most common methods used to analyse the effect of the ground, groundwater and surcharge loads on segmental lining in conformance with standards and guidelines from various countries in Europe, Asia and America are: Elastic Equation Method, Beam Spring Model, Finite Element Method and Discrete Element Method.

The most common special loads that are usually taken into account are loads induced by earthquakes, fire, explosion or adjacent tunnels. It is of great importance to underline that every project must be exhaustively designed according to its own boundary conditions in terms of not under or oversize it. Furthermore, the aim must be always looking for the optimal technical design and the most favourable price.

In the current section, an overview of all the possible loading cases that a segment is exposed to since its manufacturing until its serviceable stage is given. However, from now on, the project is only focused on the construction phase. In the following section, a state of the art regarding to the most common segment damages and their possible causes will be exposed in a more accurately way.

2.3.1 Segment damage during construction phase

The construction phase of a tunnel, is the most aggressive phase for the tunnel linings. They are exposed to many kinds of external effects, which can cause different types of damage. These damages and how to avoid them must be studied in detail as their consequences can cause several durability and stability problems such as, permeability of liquids inside the cavern or even structural fail.

The main external effects are exposed in Figure 2.9, some of them are explained in more detail later in the section as they are of great importance for the developing of the present study. The section starts with an overview of all the possible external and internal effects on the segments during construction phase. Continues with the description of the most common damages according to a research done by the Japan Society of Civil Engineers and concludes with an explanation of the possible damage causes.

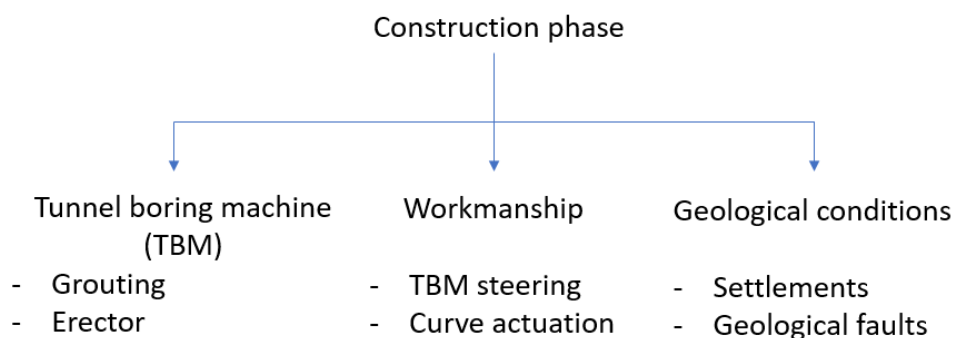


Figure 2.9 Construction phase damage causes

One of the main problems in tunnel lining, that is not an external effect but an effect of interaction between the segments, is the joints. The areas of interaction between segments are the joints, there are the ring and the longitudinal joints. As tunnels are often very long, there are thousands of joints per lineal meter forming the longitudinal cylinder. These joints can directly affect the structural behaviour of the tunnel as well as enable liquid permeability.

On the other hand, an important fact that has also to be considered in the developing of damages during construction is the workmanship of the TBM driver. A good knowledge and experience in the field of the TBM driver can play a significant role in the assembling of the segments.

In the present study, the effect of the geological conditions of the ground is not covered, as in terms of stress development in the lining it is usually not the main influencing factor. However, it is of great importance to mention that the ground conditions can highly influence how to proceed with an excavation with TBM.

This section gives a state of the art of the most common segment failures and their corresponding causes during construction phase according to recent research.

Types of most common segment failures

In construction stage, different kind of damages are developed throughout the segment. A survey carried out by 15 major experienced general construction companies, provides the data of 50 sites that was used by the Japan Society of Civil Engineers (JSCE 2005) to establish a classification of the crack patterns and failures in the segment. These 50 sites had all the same following characteristics:

- *The grounds at the tunnel are distributed from soft alluvial layer to stiff diluvial layer.*
- *About 80% of minimum radius of the tunnel alignment is larger than 50m.*
- *The diameters of TBM have a range from 3m to 10m.*
- *About 90% of the target segments are RC segment with less than 1.5m width.*

In the report of Causes of shield segment damages during construction (Sugimoto 2006), a summary of the questionnaire survey is exposed. A compilation of the main ideas is described below.

Classification of the segment's damage during construction. Most common crack patterns and failures (Table 2.1):

Table 2.1 Most common segment damages in tunnel segments (JSCE,2005)

No.	Segment damage	Figure	No.	Segment damage	Figure
1	Crack in axial direction		6	Crack/stripping around ring joint box	
2	Crack in circumferential direction		7	Crack/stripping around segment joint box	
3	Chipping at segment corner		8	Stripping at outer surface	
4	Stripping around segment joint		9	Hair crack at inner surface	
5	Stripping around segment joint		10	Appearance of non-visible cracks	

Results of the survey

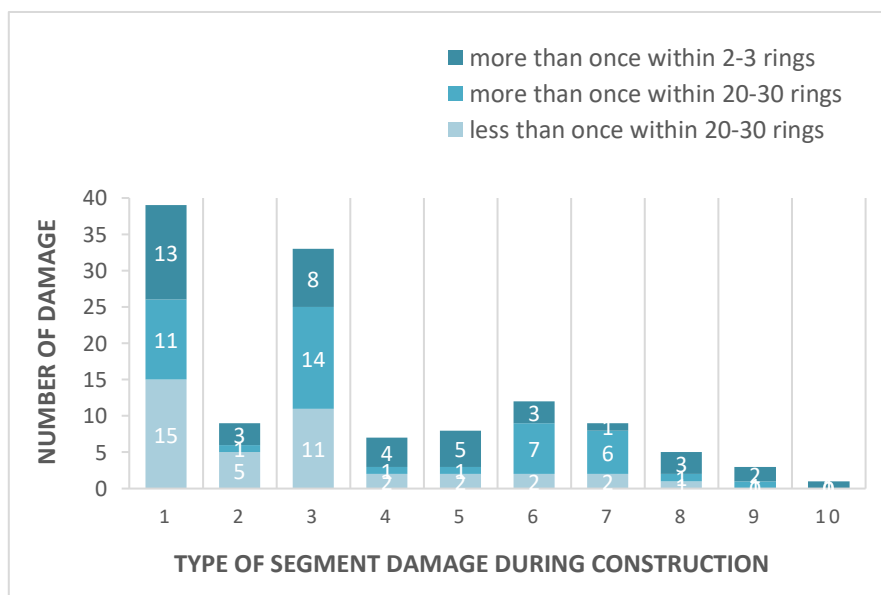


Figure 2.10 Frequency of segment damage during construction (JSCE 2005)

In Figure 2.10, it can be seen that the most common failure in tunnel segments are cracks in axial direction (1) and chipping in the segment corner (3). On the other hand, crack in circumferential direction (2) and stripping in both segment (4) and ring (5) joints are also relevant.

A TBM machine, installs the segments while it excavates. This means that the loads applied on the segments are directly related to the stages of excavation, at curve, at straight line and initial both at curve and at straight line among others (JSCE 2005).

Crack development is considered as a quality loss of the lining as it increases the probability of leakage and influences on the deterioration which results in high maintenance costs. The experience in the field shows that the cracks mostly appear during the installation process and arise in the concrete in reduced areas such as the bolt pockets and handle holes, the segment corners, where the jacks apply the axial forces and near the longitudinal joints (Blom 2002).

Since crack phenomena determines a quality loss in the lining, it is important to reduce it as much as possible. A possible way to do so is by using an appropriate configuration of the thrust jacks and supports. On the other hand, a crack reduction in the lining can occur due to the improvement of the reinforcement with SFRC. An optimal combination of SFRC and conventional reinforcement localized in proper regions can substantially improve the crack behaviour of the lining (Plizzari and Tiberti 2006).

Causes of damage and crack patterns

In terms of optimizing the design of tunnel linings, the main causes of segment failure must be detected. In the following table, the main causes during construction stage according to recent research are presented (see Table 2.2).

Table 2.2 Segment's damage causes

Cause		Cause	
HYDRAULIC JACKS	<i>Excess of thrust force</i>	TBM STEERING AND CURVE ACTUATION	<i>Unequal ring axial deformation</i>
	<i>Eccentricity of the jack</i>		<i>Unequal lateral friction resistance</i>
	<i>Inclination of the jack</i>		<i>Not axial direction of the jack thrust</i>
GROUT PRESSURE	<i>Tail skin grout pressure</i>	TRUMPET SHAPE	<i>Unequal ring joint support</i>
	<i>Secondary grout pressure</i>		
CIRCUMFERENTIAL JOINT	<i>Uneven support with adjoining ring Coupling effects</i>	LONGITUDINAL JOINT	<i>Rotational stiffness Geometrical and assembly tolerances</i>

A further research among segment damage causes has been done. In the following sections, some possible causes will be described in a more accurate way.

Hydraulic jacks

In a TBM excavation process, the advance of the cutterhead and the shield itself is carried out by means of hydraulic thrust cylinders, called jacks. These jacks, apply a load on the previous built ring in order to push forward the shield. They are placed on bearing pads all around the circumference mostly corresponding to two or three pads per segment, depending on the jack configuration adopted.

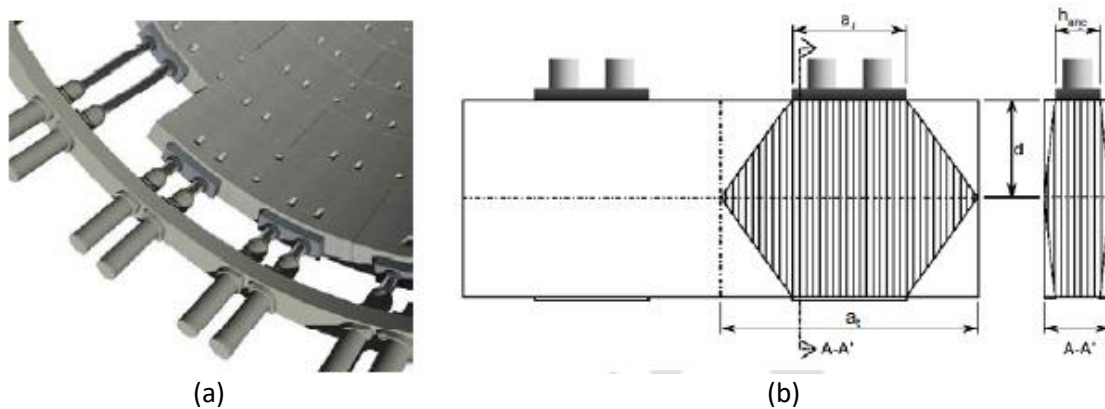


Figure 2.11 Thrust jacks (a), Schematic stress distribution (b) (ACI 544 Committee 2014)

The thrust force applied and how it is applied on the segment can lead to both structural failure due to uneven support of the adjoining ring and punctual failure due to high axial forces. High compression stresses are developed under the jack pads, as well as bursting tensile stresses inside the segment and spalling tensile stresses between the pads as it is shown in Figure 2.11 (b).

The action of the jacks in the construction stage has been studied on many occasions (Sugimoto 2006, Burgers et al. 2007, Caratelli et al. 2010, Tiberti et al. 2015, Meda et al. 2016) and the most common causes can be summarized as follows:

- Excess of jack thrust
- Eccentricity of the jack thrust
- Inclination of the jack against the segment

The *excess of the thrust jack* can lead to a severe compressive and tensile stress field on the segment and thus, the development of crack patterns. The excess of thrust can be due to the necessity to exceed the protocol limitations in order to proceed with the excavation or due to curve actuation and TBM steering.

Sometimes, thrust jacks may not be exactly on place, this *eccentricity* can cause problems such as crack patterns or local splitting behaviour under the loading pads. It is shown in Figure 2.12 that with eccentricity, the ultimate load decreases substantially. Because of the eccentricity, the segment tends to tilt outwards and provide a non-smooth support and as a result a bending moment occurs (Burgers et al. 2007). The eccentricity can be originated due to previous deformation of the ring where the jacks are supported or due to curve actuation (Blom 2002).

The *inclination of the jack* may lead to a non-flat contact with the segment which will develop a bending moment.

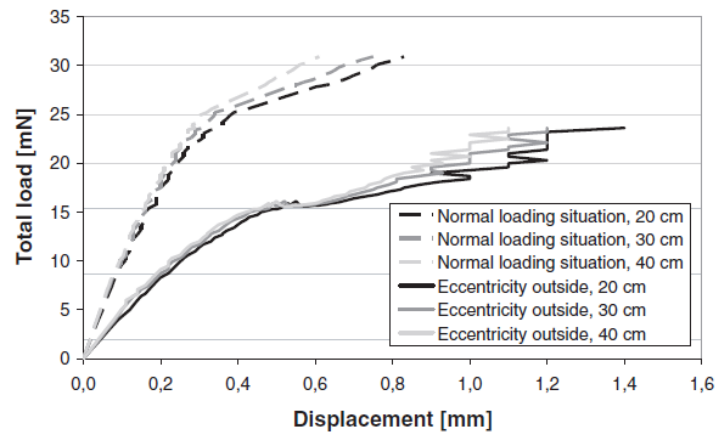


Figure 2.12 Development of splitting stresses under the load (Burgers et al. 2007)

Grout pressure

In the excavation process, the excavated diameter is larger than the tunnel lining external diameter. This void between the soil and the tunnel lining is filled with a semi-liquid grout to ensure the embedment of the lining and control the surface settlements.

The type of injected material depends on the soil characteristics. In the case of hard rock, the annular gap is backfilled with pea gravel instead of grout. However, in the case of soft soils, a grouting material is injected. The grout is a visco-plastic material that presents a change on its rheological properties with the time. The most typically used grouting materials are hydraulically setting mortar and two-component grout.

The mortar should present an excellent pumpability in early stages in order to minimize plugging problems in the grout system. However, the mortar should also present a certain grade of stiffness to ensure a good embedment of the lining. The two-component grout was developed to achieve a good pumpability and workability during injection and a quick setting when placed around the lining. One component is a cement bentonite slurry and the other a hardener or activator (Thewes and Budach 2009).

There are two different methods to inject the grouting material in the gap between the ground and the lining. On the one hand, there is the grouting through grout holes in the lining segments. It consists of holes in the segments with non-return valves or plugs to retain the grout in the annular space. On the other hand, there is the grouting through the tailskin. With this method, the mortar is pumped through pipes and injected in the tailskin part of the shield (see Figure 2.13).

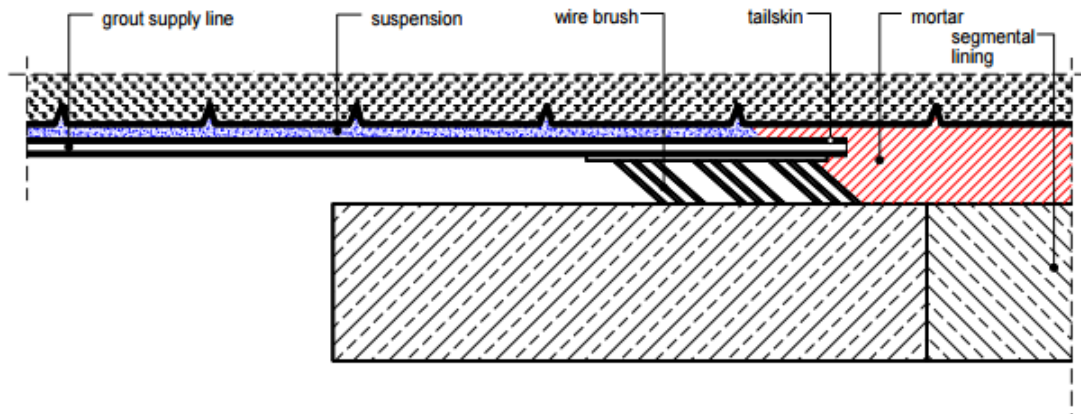


Figure 2.13 Grout injection through tail skin (Thewes and Budach 2009)

Grout injection is essential to ensure a good performance of the tunnel. However, it can cause some problems in terms of tensions in the segments, which are directly in contact with it. According to Cavalaro (2009) and the tests done in the Madrid metro line 6 and Barcelona metro line 9, the most critical moment in terms of tensions applied by the grouting to the segments is when the ring goes out from the tailskin of the shield. As time goes by, the variation of pressure tends to decrease until it achieves a certain stability.

The main loading case according to ACI Committee 544 (2014) is described below. The loading case is related to the tailskin injection method. There is another loading case mentioned in the ACI Committee 544 related to the injection method through segment holes. However, due to collapse of unstable ground in the lining and settlements in the surface before performing radial grouting through segment holes, this method is only used for check grouting.

Tail skin grout pressure

Grout pressure can be responsible for the development of tensions in the segments. Therefore, it must be limited to a value slightly higher than the water pressure but lower than the overburden pressure. Otherwise, it may result in the push off of soil towards the ground surface.

Considering the following parameters, the groundwater level, the plastic consistency of grouting, the advancement rate of shield tunnelling and the filling rate of the tail void, grouting models are developed to determine the minimum grout pressure permitted. The equivalent specific weight of the grout is calculated through equilibrium between the upward component of the total grout pressure, the tunnel deadweight and the tangential component of the grout shear stresses. This equilibrium forces are schematically shown in Figure 2.14.

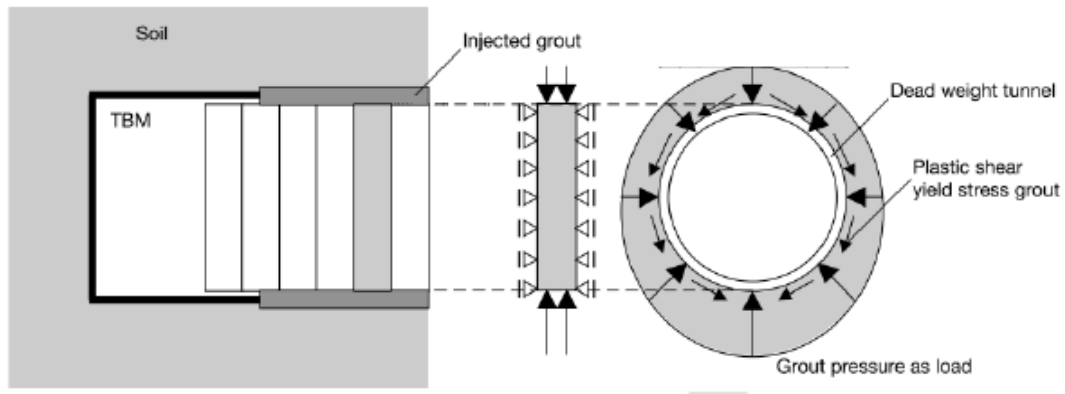


Figure 2.14 Back grouting pressure (ACI 544 Committee 2014)

In this phase, the lining is surrounded by grouting material, therefore, interaction between the lining and the ground is not considered. According to ACI 544 Committee (2014), the deadweight of the lining and the grouting pressure are the only loads applied to the lining. As a result, significant axial forces and bending moments are developed in the segments.

Joints

In the assembly process, segments are installed. They are erected by the TBM and form adjoining rings which at the same time form the cavern cylinder. The interfaces between the segments and between the rings are of great importance in terms of impermeability and stress development. The joints between segments are called longitudinal joints and the ones between adjoining rings are called circumferential joints.

The segments must be erected and collocated in such a layout that longitudinal joints are not in line for the adjoining rings. The objective of this configuration is minimizing the sealing problem when four corners coincide and avoiding the stress concentration in such spots. (Blom 2002) Usually the layout configuration is chosen by the TBM driver adopting patterns according to previous experience.

It is of great importance to underline that the two kinds of joints must be considered according to their own technical specifications as their structural behaviour is different. In the following sections both kind of joints are described.

An important issue that must be also described is the design of the ring, which is directly related to the layout configuration and the behaviour of the joints. There are different kinds of ring designs, however, the most widely used today is the symmetric universal ring. The universal ring has a different width around the circumference in terms of adapting itself to the different radius of curvature of the tunnel layout. The minimum width is in the key segment and the maximum in the opposite of it. The difference of width between the key segment and the opposite is of 100 mm, \pm 50 mm from the centre of the segment.

Until recently, all the longitudinal joints were radial except the oblique ones of the key segment. The key segment has a trapezoidal shape and recently in some projects, this trapezoidal shape has been extrapolated to the rest of the segments as it seems to bring a more even support due to the facility of assembly.

Circumferential joints

Circumferential joints are the contact areas between adjacent rings and because of them, the use of packing materials is necessary. However, the properties of the packing materials and their force conditions might result in shear resistance between the circumferential joint while the adjoining rings deform differently. This shear resistance acts as radial and tangential forces (Blom 2002). In some tunnel projects, where soil conditions are bad, a dowel and socket system is applied in circumferential joints in terms of preventing too large deformation differences between adjoining rings (Arnau and Molins 2012).

To prevent the penetration of water inside the cavern, rubber gaskets are glued in the circumferential joints of the adjoining rings. Thanks to the compression of the gaskets due to the axial forces introduced by the jacks, leakage is prevented. In terms of ensuring the sealing of the circumferential joints and keeping the segments together while jack thrust is applied, temporary pre-stressing bolts are used.

Segments are designed and manufactured with size tolerances. In practice, it is recommended to use big tolerances as they do not require such high accuracy in manufacturing, which is directly related to the cost (Cavalaro 2007). It is important to note that the tolerances are of great importance for the joints as they must be big enough in order to facilitate the assemblage but not too much in terms of costs. However, if these tolerances are not well designed and they result in being too small, stress development might occur. An example of tolerances is the one showed in Figure 2.15 from the dowel and socket connection.

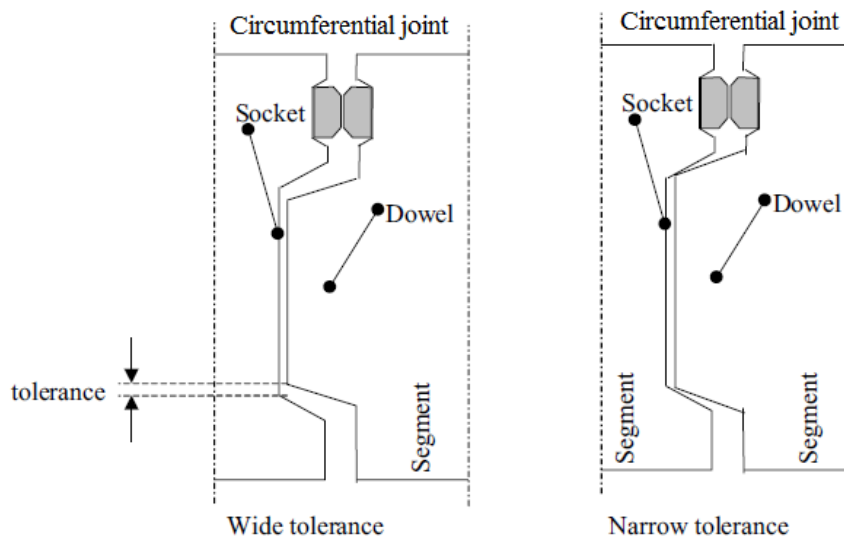


Figure 2.15 Dowel and socket connection tolerances (Blom 2002)

During the assembly process, due to the sequential loading of the rings, shear resistance is developed in the circumferential joints. This results in a three-dimensional deformation of every ring which will provide an uneven support for the hydraulic jacks' axial forces. As a consequence, additional stresses are developed in the segments and crack patterns might occur.

This unevenness might occur due to several reasons, for example, the unequal adjoining jack forces around the circumferential joint, the global bending moment due to the TBM steering, the elastic and plastic deformation of packing materials and the unequal deformation of the rings.

A possible cause of the three-dimensional deformation of the rings are the so-called coupling effects due to the differences between the vertical and horizontal pressure of the ground. Commonly, the horizontal stress is smaller than the vertical stress and this results in an ovalization of the ring in order to equilibrate the reaction to the loading. As a result, relative radial displacements and tangential forces between adjacent rings occur (Arnau and Molins 2012).

Longitudinal joints

The contact areas between the segments of a ring are called longitudinal joints. Tangential forces are developed in the joint in a concentrated way due to the reduced thickness of the contact area comparing to the segment thickness. According to Blom (2002), longitudinal joints behave like concrete hinges when adjoining segments try to rotate against each other. The problem is that bending moments are developed due to the resistance against rotation (rotational stiffness) of the segments.

Longitudinal joints present a complex non-linear behaviour as they are not able to transfer tensile stresses (Blom 2002). An increasing bending moment occurs for a certain axial stress level and as a result a loss of contact between segments takes place at one side of the joint. The loss of contact generates a non-linear behaviour that depends on the axial stresses (Arnau and Molins 2011).

The introduction of the interactions between adjacent segments (longitudinal joints) in the models that try to define the structural response of the lining has been a much-debated topic. A few models consider the longitudinal joints behaviour by means of rotational springs (JSCE 2000, Blom 2002), however, according to Arnau and Molins (2011), the most accurate model that introduces the non-transmission tensile stresses effect is the method carried out by an approach with FEM (Finite element method) (Plizzari and Tiberti 2006).

As in circumferential joints, gaskets are used to provide the sealing of the joints. They must be well compressed in order to provide a good performance. Pre-stressed bolts are also used in longitudinal joints to ensure the locking and keep the segments together when hydraulic jack forces are applied. These bolts are later removed to avoid corrosion and to minimize costs.

TBM steering and curve actuation

Workmanship is directly related to the quality of the final result in every mechanical procedure. That is why, is of great importance to mention that the steering of the TBM carried out by the driver is a hard and delicate job. Despite the fact that the TBM steering is currently quite automatized, the role of the TBM driver is still very important in some specific aspects that can be decisive for the structural behaviour of the tunnel lining.

The steering of the TBM is carried out by means of hydraulic jacks. Depending on where the maximum force is applied around the circumference, the TBM will be able to excavate in curve. The same principle is applied in the following case. As the shield is very heavy, it tends to tilt downwards and in order to keep the drilling face in axial direction, jacks apply a higher force at the bottom side of the ring. Another factor that can influence on the thrust forces is the rotation direction of the drilling face. Consequently, the axial deformation of rings is unequal,

the lateral friction resistance is unequal and the direction of the introduction of the jack forces might present some eccentricity.

As previously mentioned, the layout configuration is chosen by the TBM driver adopting patterns according to previous experience. However, an important decision related to the layout configuration is the placement of the key segment. The position of the key segment is chosen strategically following two basic rules. The first rule consists on avoiding certain forbidden positions, which are those that create crossed joints or small areas between the longitudinal joints of each ring and the circumferential joint of the adjacent rings. The second rule consists in placing the key segment where there is the maximal radial distance between the extrados of the last assembled ring and the internal side of the shield along the lines of a vertical and a horizontal diameter, as it is shown in Figure 2.16.

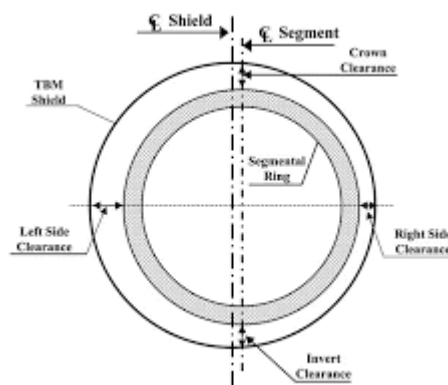


Figure 2.16 Criteria for position of the key segment
(Personal contribution of J. Ainchil)

The placement of the key segment can be also critical in terms of the available space where it has to be placed, as it can be either too large or too small. On one hand, when the space is too large, a gap remains between the adjoining segments and thus deformations might occur when the thrust of the jacks is applied. On the other hand, when the space is too small, the key segment is forced to fit inside the gap and crack patterns in the adjoining segments might occur.

Trumpet shape

As the TBM advances, hydraulic jacks are supported on the last installed ring. The last ring is assembled with the previous adjoining rings, which are already loaded in radial direction due to several reasons such as the grouting material injected. As a result, these rings are deformed. Due to the presence of axial forces, friction resistance occurs in the circumferential joints.

In the case of the last assembled ring, radial forces act partially on it. Due to this partially radial loading and the friction resistance in the circumferential joint, a three-dimensional deformation called “Trumpet shape” takes place (Blom 2002). The mechanism of the trumpet shape is in Figure 2.17 presented.

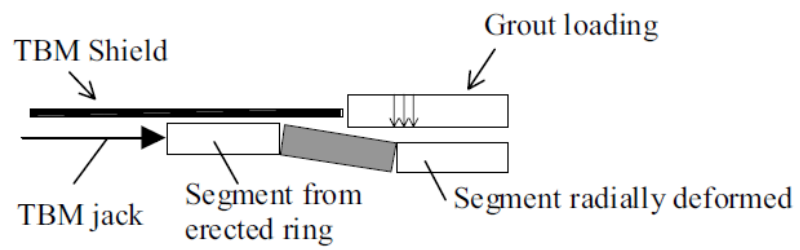


Figure 2.17 Trumpet shape (Blom 2002)

3. STUDY OF UNEVEN SUPPORTS IN TUNNEL SEGMENTS

3.1 INTRODUCTION

The installation process of the segments that create the lining of the tunnel can be one of the most damaging stages for these precast concrete pieces. There are several kinds of external effects that can directly influence the quality of the segments in terms of crack development and failure. These external effects can be induced by the TBM, for example, through the hydraulic jacks or the erector.

However, this chapter is focused on the effect caused by the structural response of the collocation of the segments. The structural behaviour of the segments in response to the boundary conditions, can cause non-smooth supports for the next installed segments.

The aim of this chapter is to identify the most representative cases of uneven supports and study the development of the stresses which can lead to failure in the segments. In some of the cases, data of real tunnels is analysed and compared in order to extract any relevant conclusions.

The considered scheme of the segments in the study is the one in Figure 3.1. The segments are divided into the ones that create ring “i” and the ones that create ring “j”. Ring “i” corresponds to the ring where the axial forces from the hydraulic jacks are applied and ring “j”

corresponds to the support of ring “i”. The development of stresses will be calculated for segment “i” considering the boundary conditions imposed by the adjoining segments.

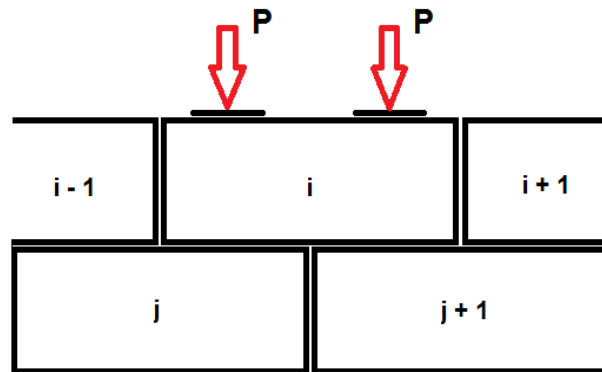


Figure 3.1 Perfect configuration of the segments

The calculation of the stresses is carried out by means of the so-called Strut-and-tie method for a deep beam. This basic method gives a good approximation for the stresses and consists in representing a compatible configuration of the stresses developed in the segment, making the difference between struts (compression stress) and ties (tensile stress).

In the following diagram, the main uneven support cases are described according to criteria based on real cases in the construction sites. The cases are divided into the ones which the uneven support is caused by a displacement of segment “j” and the ones caused by a turn of the segments “i”, “j” and “j + 1” as it is shown in Figure 3.2.

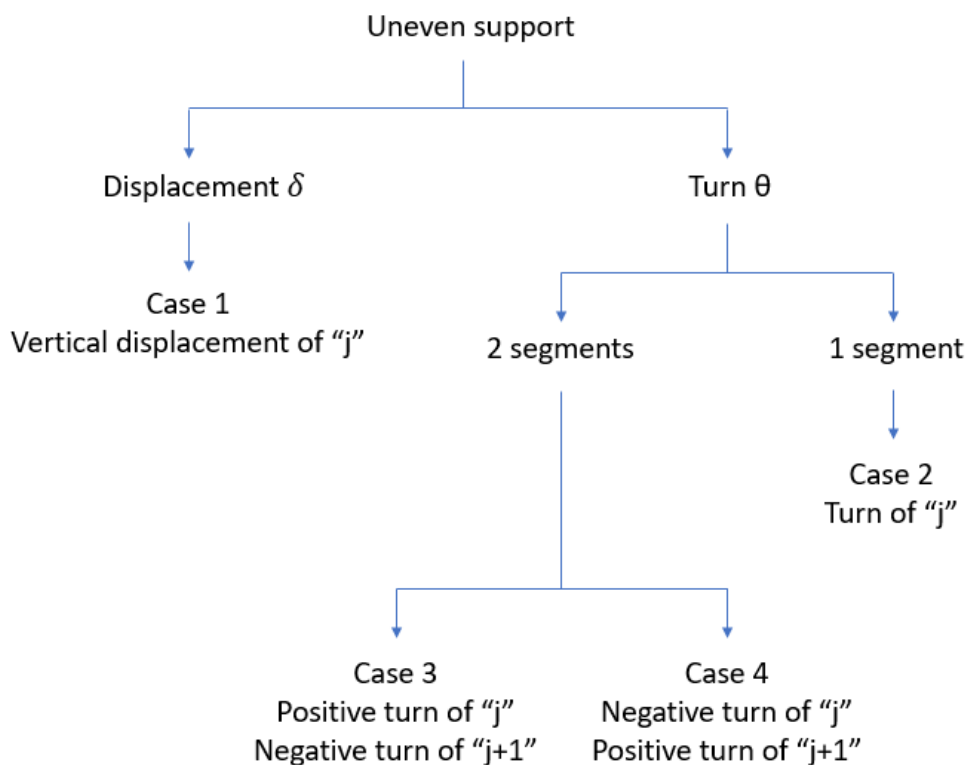
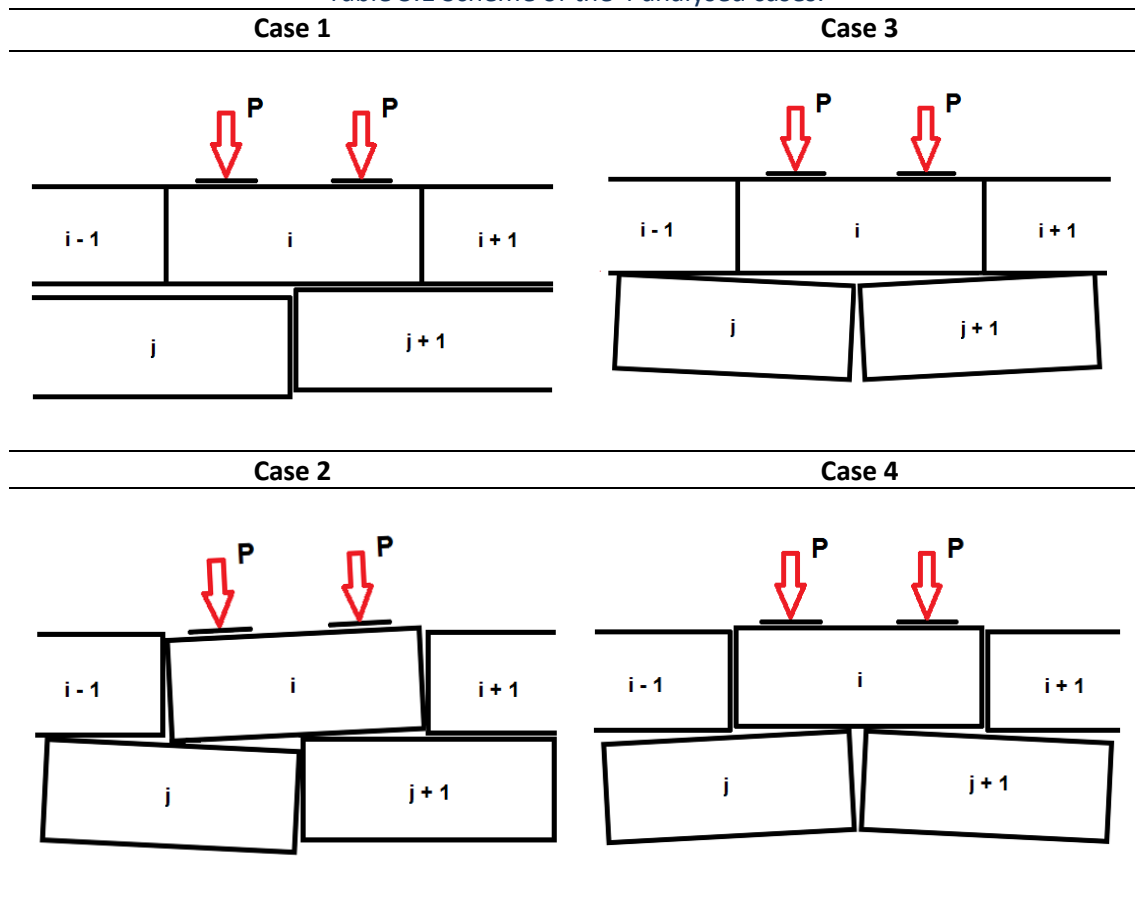


Figure 3.2 Cases of uneven supports of the segments

In Table 3.1 a scheme of each case is presented.

Table 3.1 Scheme of the 4 analysed cases.



In the following sections, a brief approach to the causes of uneven supports and the calculation bases considered in the study are presented. Finally, a deeper explanation and investigation of each case is done, identifying the stress fields and proposing the optimization of the reinforcement with steel fibres.

3.2 CAUSES OF UNEVEN SUPPORTS

During the construction process of the tunnel lining, the contact between the adjacent rings and segments may not be perfect. Although these irregularities in the contact areas are often quite small, they can compromise the structural behaviour of the tunnel lining.

Controlling and identifying the causes of these irregularities is not an easy task, due to the great number of influencing factors and their complexity. According to Cavalaro (2009), the formation of irregularities in the contact areas between the longitudinal and circumferential joints is mainly due to the project approaches considered and the manufacturing and collocation tolerances of the segments.

Due to the structural response of the lining acting as a whole, factors such as accumulation and propagation of irregularities must be also taken into account. This phenomenon induces an increase of the irregularities among the already installed rings and segments. In Figure 3.3 the mechanism of accumulation of irregularities is shown. It must be highlighted that the sketch is not to scale.

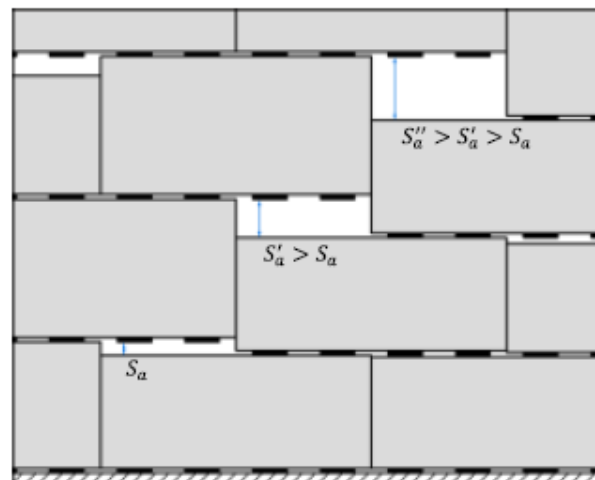


Figure 3.3 Accumulation of irregularities among adjoining rings. (Cavalaro 2009)

As mentioned in chapter one, the effect of hydraulic jacks can have a great influence on the behaviour of the lining, mostly in the last installed rings. Factors such as, the curve actuation or the forehead lifting of the TBM, make the pressure of the jacks not exactly equal among the ring. This variation of the pressure between segments may induce to an unequal support for the next ring.

3.3 CALCULATION BASES

This study aims to identify the main stresses developed in a tunnel segment. The stresses are responsible for the cracking behaviour in the segments and compromise the quality of the tunnel lining in terms of structural stability and penetration of liquids. To do so, the segment is idealised as a deep beam due to its dimensions and its stresses calculated through the so-called Strut-and-tie method.

Deep beam

A beam shall be deemed to be a deep beam when the ratio of effective span to overall depth is less than:

- 2,0 for simply supported beams
- 2,5 for continuous beams

There are different considerations and codes for deep beams in terms of span-to-depth ratios. However, as a general rule, deep beams are recognised by their relatively small span-to-depth ratio. An important issue regarding deep beams is that the Navier-Bernouilli assumption

is not applicable to them. The structure or parts of the structure that do not follow the general theory of flexure, where the Navier-Bernoulli assumption is not applicable, are the so-called D-regions.

Strut-and-tie Method

The Strut-and-tie model approach is a suitable design method for shear members and D-region structures. This approach can provide a method that makes a quite complicated concrete structure to a simple truss model. That is why, in the present study, the identification of the stress paths in the segments is held by the strut-and-tie method.

The strut-and-tie model is a discrete representation of actual stress fields in a structure resulting from applied loads and support conditions. The model represents the load-transfer mechanism of a structural member by approximating the flow of internal forces through struts and ties, that represent the flow of compressive stresses and the flow of tensile stresses respectively. As it is shown in Figure 3.4 struts and ties are connected at nodes to form an idealized truss and the struts can be represented by prisms or bottle-shaped elements. (ACI 318M-14 2014)

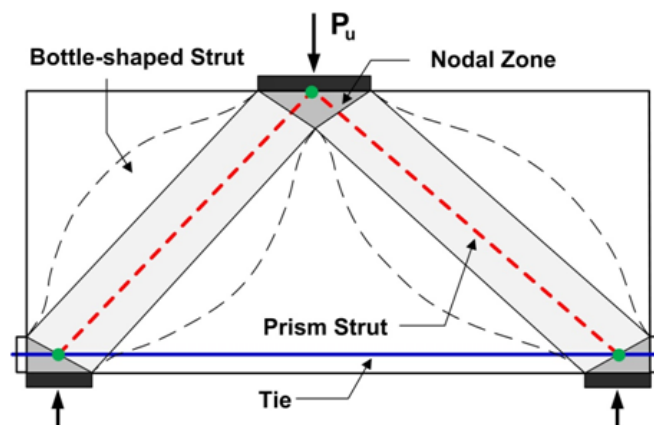


Figure 3.4 Strut-and-tie model for a deep beam.
(ACI 318M-14 Fig. R23.2.1 2014)

Assumptions of the present study

The structural behaviour of the tunnel lining is a complex mechanism with a lot of influencing factors that can lead to crack development or structural failure. That is why, the present study aims to analyse these influencing effects individually and tries to extrapolate the results to a bigger scale approximation of the behaviour.

In the process of installing the segments, there are two critical moments for the segments in terms of loading. The first one is when the segment is still not completely embedded in the ring as the segment “i + 1” is not placed yet (Figure 3.5). In this situation, there is no support in the right side of the segment and the hydraulic jacks apply the force to sustain the segment in its place. The other situation is when all the segments conforming a ring are pressed in order to push forward the shield and keep excavating the front.

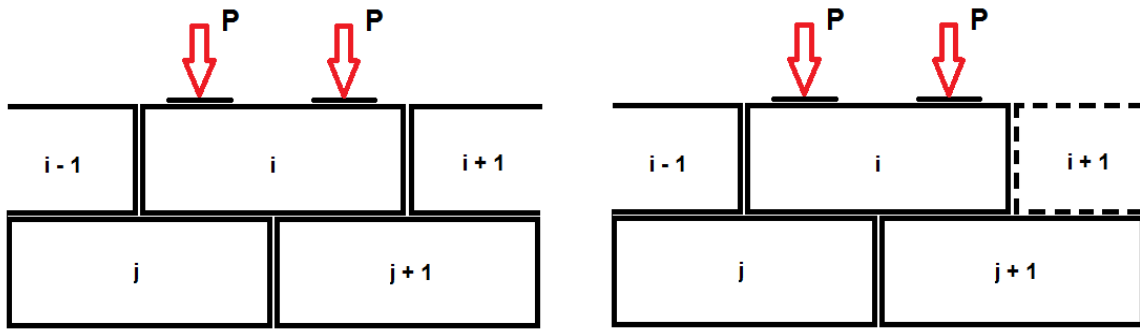


Figure 3.5 Ideal configuration for both cases, with and without “i + 1” segment.

In this section, the analysed effects are the uneven supports present in the adjoining rings and segments. This unevenness in the joints induces the appearance of critical stress fields in the segments which can compromise the quality of the tunnel lining.

To do so, in the analysis, the following assumptions are considered:

- The geometry of the tunnel segment is the one shown in Figure 3.6. It must be underlined that the longitudinal joints are straight and not oblique.

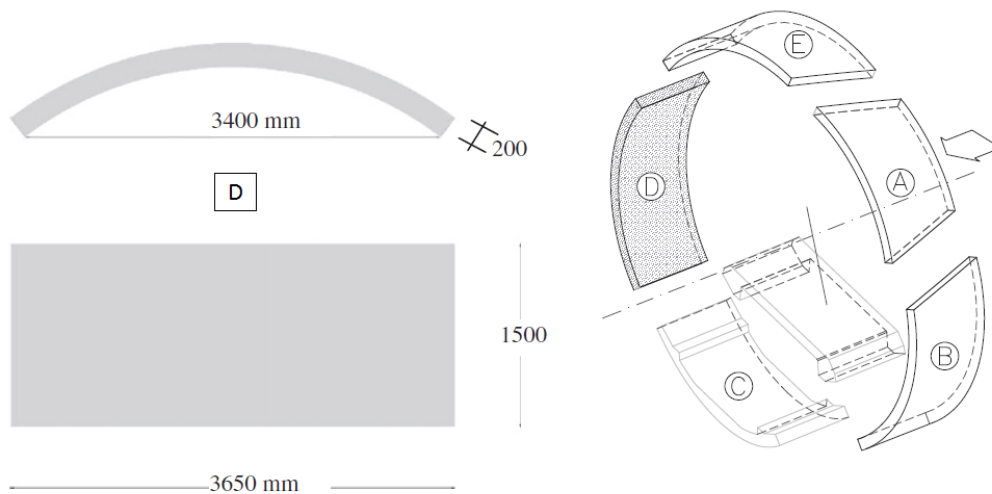


Figure 3.6 Tunnel segment geometry example (Caratelli et al. 2010)

- The considered value of the hydraulic jack’s force P is taken from a Middle East Metro Line TBM as an average value.

Conventional situation = 5500 KN

Accidental situation = 6500 KN

$$P \cong 6500 \text{ KN}$$

- The configuration of the hydraulic jacks corresponds to two jacks per segment as shown in Figure 3.7.

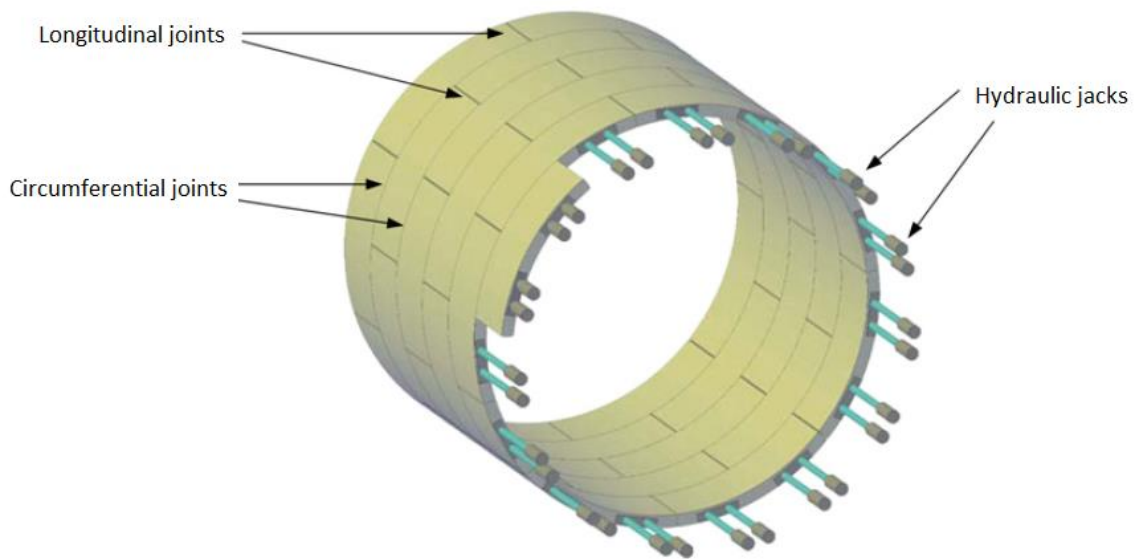


Figure 3.7 Hydraulic jacks' configuration.

- The interaction between longitudinal joints in terms of friction is not taken into account in this section. However, an exceptional situation is analysed in case 2. This consideration will give the worst scenario for the segments as all the force is transmitted to the circumferential joint.

With the previous considerations, the chapter proceeds with an individual analysis of the cases exposed above. The stresses developed in each case will be carefully analysed by means of the Strut-and-tie method in order to identify the most dangerous scenarios.

3.4 PRACTICAL CASES

3.2.1 Case 1 Vertical displacement of the support segment

The first case consists of the uneven support of the segment that is being installed due to a vertical displacement of one of the segments that corresponds to the previous ring. This displacement causes a small step between two adjoining segments of the ring which will produce a discontinuous support for the next ring.

In this case, it is considered that the installed segment is only in contact with one of the segments of the supporting ring. As in this chapter the effect of the longitudinal joints is not considered, in this scenario is not necessary to make the difference between the case with and without segment "i + 1".

As it is shown in Figure 3.8, the representation of the stresses is carried out by means of a strut-and-tie model considering two supports in the lower part of the segment. In this scenario,

the tensile stresses developed in the upper part of the segment, between the bearing pads, are the most dangerous ones that can lead to the formation of longitudinal cracks.

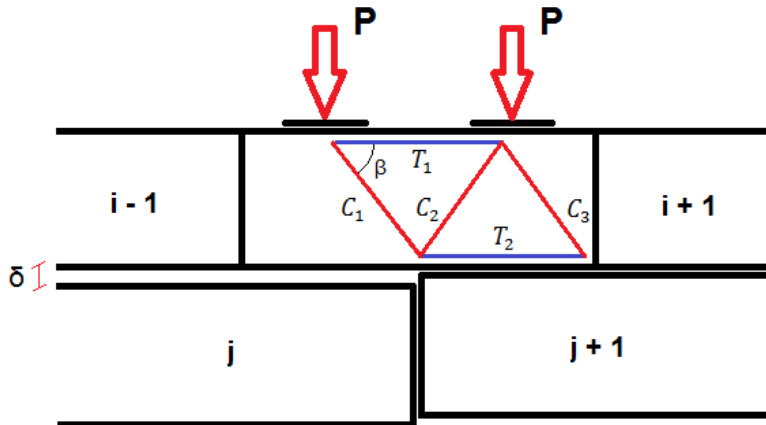
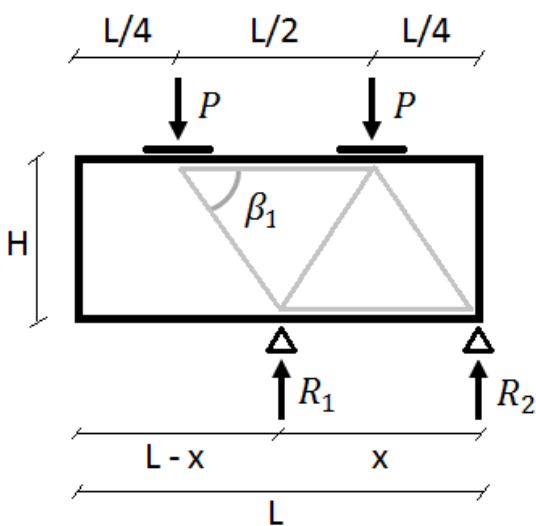


Figure 3.8 Strut-and-tie scheme case 1

In order to proceed with the calculation of the stresses, the geometry of the segment must be specified first. As it is shown in Figure 3.9 the angle $\beta_1(x)$ between the strut and the tie depends on the eccentricity of the support 1 (R_1).

Geometry of the segment i



Equilibrium equations

$$\beta_1 = \tan^{-1} \left(\frac{H}{\frac{3L}{4} - x} \right) = \beta_1(x)$$

$$R_1 = P \cdot \frac{L}{x} ; \quad R_2 = P \cdot \frac{2x - L}{x}$$

(1)

Compatibility equation

$$\epsilon_c = \epsilon_s$$

(2)

Figure 3.9 Geometry of the segment, equilibrium equations and compatibility equation

Calculation of the stresses through the strut-and-tie method

In accordance with the equilibrium equations (1) and the compatibility equation of strain (2), the following relations are presented:

$$T_1 = C_1 \cdot \cos \beta_1 \tag{3.1}$$

$$P = C_1 \cdot \sin \beta_1 \rightarrow C_1 = \frac{P}{\sin \beta_1} \quad (3.2)$$

$$T_1 = P \cdot \frac{\cos \beta_1}{\sin \beta_1} = P \cdot \cot \beta_1 \quad (3.3)$$

With the previous equations, it is possible to estimate the value of the tensile stress T_1 depending on the eccentricity of the support 1 and the force applied by the hydraulic jacks. In the following section, particular cases will be analysed and compared in order to draw any relevant conclusions.

Particular cases and comparison

In this section, some real cases of tunnels are analysed and compared. With equation (3.4) and the data available in Table 3.2 a graph of the tensile stress $T_1(x)$ in terms of the support eccentricity and the hydraulic jack's pressure P for every tunnel is plotted.

- Equation $T_1(x)$

$$T_1(x) = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{\frac{3L}{4} - x} \right) \right) \quad (3.4)$$

- Data of existing tunnels

For the analysis of the particular cases, the following geometric characteristics in Table 3.2 from six existing tunnels are considered. The data was carefully chosen in terms of having a wide range of segment sizes and tunnel diameters. The tunnels are sorted by its diameter \emptyset . This variety of data enables the comparison between them and the extraction of possible relationships between the parameters.

Table 3.2 Real tunnels data

Tunnel	P [KN]	\emptyset [mm]	H [mm]	L [mm]	e [mm]
Fontsanta-Trinitat	6500	5200	1400	3210	250
Metrorex Boltari	6500	5700	1500	3534	300
Middle East Metro Line	6500	8700	1600	4489	350
Sants-Sagrera	6500	10400	1800	5347	380
Ave Trinitat-Montcada	6500	10400	2000	5244	450
M30 Madrid	6500	13450	2000	4631	600

- Range of eccentricity "x"

The position of the longitudinal joints between segments has some restrictions as it is explained in the previous chapter. In terms of confinement and stability of the segments, the

position of the longitudinal joints in a ring cannot coincide with the longitudinal joints of the previous installed ring. Taking into account this restriction, in the present study, the position of the support is also limited in a range from $L/2$ and $L/4$ (Figure 3.10).

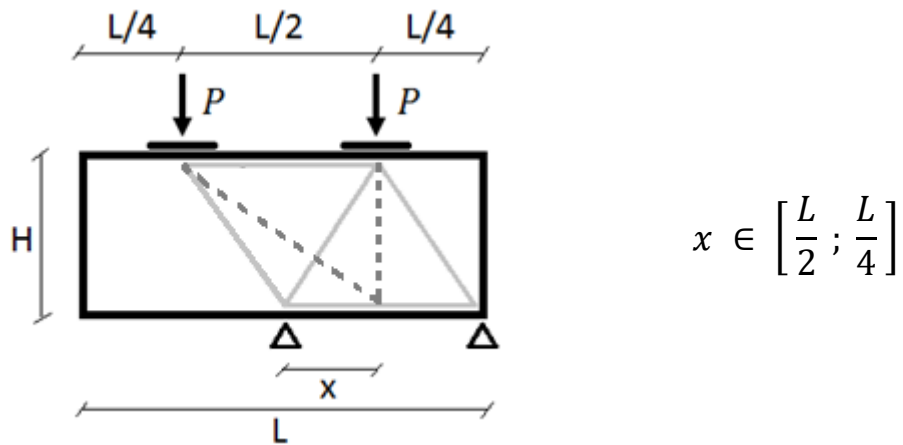


Figure 3.10 Range of eccentricity “x”.

- Plot

Making use of the data available in Table 3.2 and the equation previously calculated (1), the graph in Figure 3.11 plots the function of the tensile stress $T_1(x)$ in terms of the longitudinal joint’s eccentricity and the hydraulic jack’s pressure P for every tunnel.

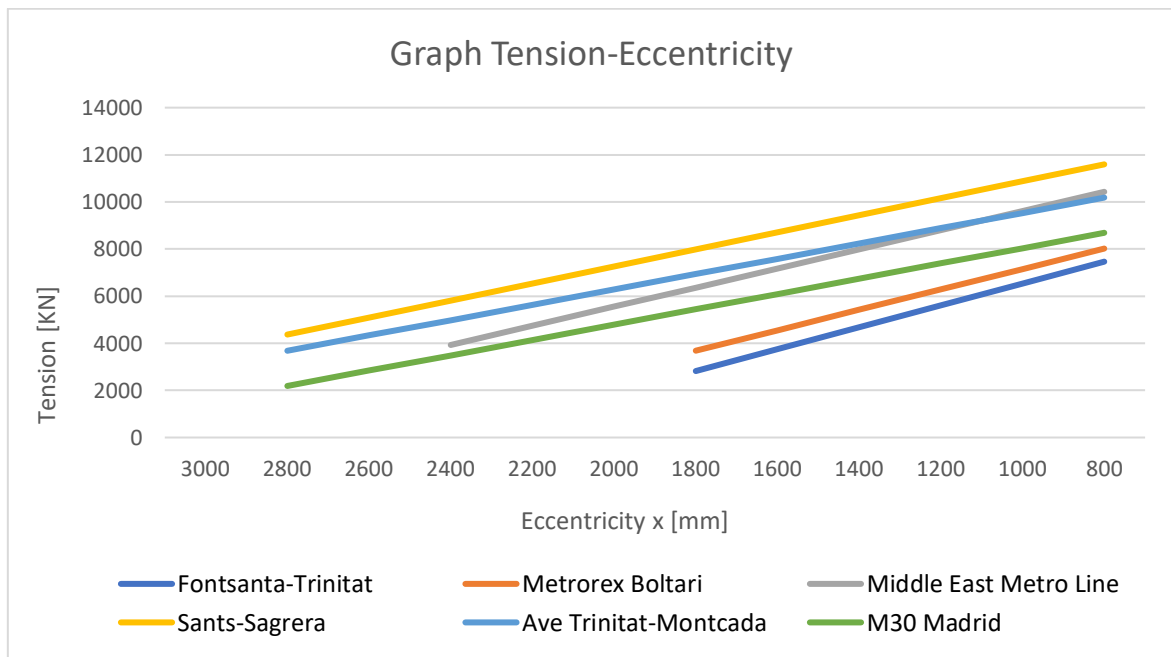


Figure 3.11 Tension-eccentricity diagram for the 6 particular cases.

As can be seen in Figure 3.11, the tensile stress function $T_1(x)$ is a linear function of the eccentricity “ x ” where “ m ” is the slope and “ A ” the cross with the Y-axis (See equation 3.5). The range of the eccentricity is restricted for every tunnel in terms of showing only the range that makes sense in every case. Below, the equation for every tunnel is presented.

$$T_1(x) = mx + A \quad (3.5)$$

Fontsanta-Trin.	$y = 928,6x - 3679,5$;	Sants-Sagrera	$y = 722,2x + 2925,9$
Metrorex Boltari	$y = 866,7x - 2381,2$;	Ave Trinitat-Montc.	$y = 650x + 2382,3$
Middle East ML.	$y = 812,5x + 677,4$;	M30 Madrid	$y = 650x + 888,1$

As shown in Figure 3.11, the three tunnels with a smaller diameter, namely Fontsanta-Trinitat, Metrorex Boltari and the Middle East Metro Line have a bigger slope than the rest three. This means, that the tension $T_1(x)$ increases faster with the eccentricity “ x ” in the smaller tunnels. However, a clear tendency regarding the slope “ m ” and the diameter “ \varnothing ” is not specified.

In the present study, it is considered in every tunnel, the same pressure P as the aim is to compare between the different geometric characteristics of the segments. Smaller tensions occur in the smaller diameters of the tunnels Fontsanta-Trinitat and Metrorex Boltari and the bigger tensions in the tunnels of Ave Trinitat-Montcada and Sants-Sagrera which correspond to bigger diameters. However, the situation for the M30 Tunnel in Madrid and the Middle East Metro Line is a little bit different. Even though the M30 Tunnel has the biggest diameter, its segments are smaller than the ones in the other two big tunnels. This can be the cause of the smaller tensions in their segments.

To go deeper into the matter of the tensions developed in the segments, the relationship between the tensions and the geometric characteristics of the segments are analysed. The aim is to find dependences between the previously calculated functions and the geometric parameters. In the following Table 3.3 the parameters are compiled.

Table 3.3 Geometric parameters of the segments and parameters of the function $T_1(x)$.

Tunnel	A	m	L [mm]	H [mm]	L/H
Fontsanta-Trinitat	-3679,5	928,6	3210	1400	2,29
Metrorex Boltari	-2381,2	866,7	3534	1500	2,36
Middle East Metro Line	677,4	812,5	4489	1600	2,81
Sants-Sagrera	2925,9	722,2	5347	1800	2,97
Ave Trinitat-Montcada	2382,3	650,0	5244	2000	2,62
M30 Madrid	888,1	650,0	4631	2000	2,32

Between the geometric parameters mentioned above, the following relations are extracted and plotted.

- The first relation is between the slope “m” and the width of the segment “H”.

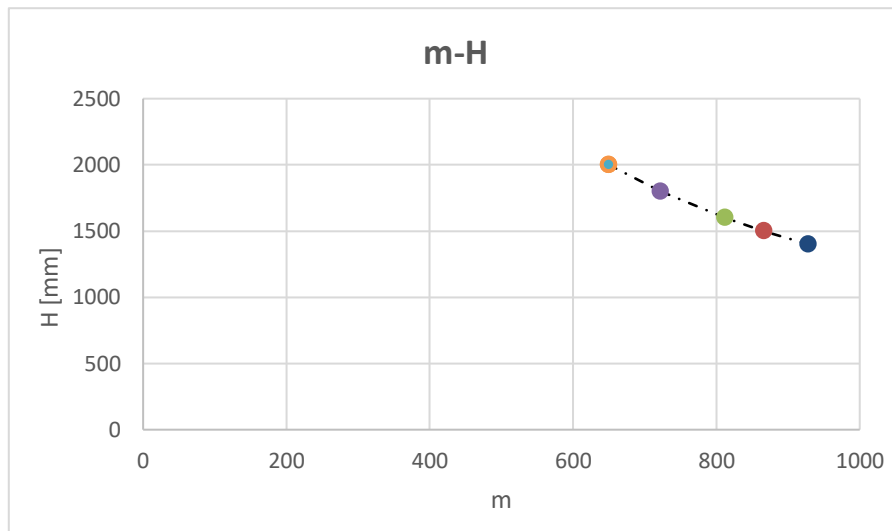


Figure 3.12 Relation between slope “m” and segment’s width “H”

As can be seen in Figure 3.12 the smaller the segment’s width “H”, the bigger the slope “m” of the function $T_1(x)$. This means that, the function $T_1(x)$ grows faster with smaller values of “H”. As a result, the tensions grow faster with the eccentricity “x” if the values of “H” are small.

$$m = f(H, \dots)$$

- The second relation is between the segment’s length “L” and the parameter “A”.

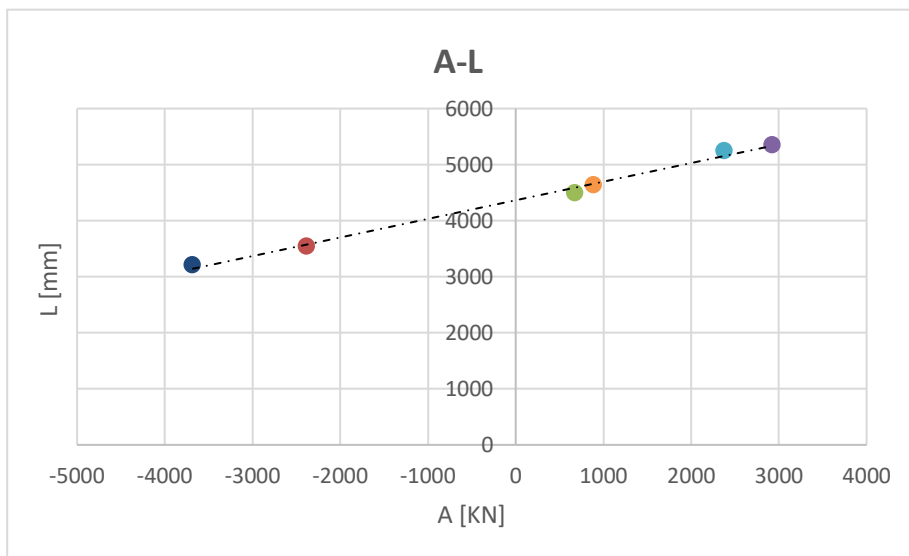


Figure 3.13 Relation between segment’s length “L” and parameter “A”

As can be seen in Figure 3.13, there is an upward trend in the relationship between the parameter “A” and the length “L”. The longer the segment, the bigger the value “A”. Value “A” corresponds to the cross with the Y-axis of the functions $T_1(x)$. This means that “A” is the value of the tension with eccentricity zero, namely the support one disappears. However, this is not a realistic situation, it gives an order of magnitude of a lower bound of the tensile stresses regarding the eccentricity of the support one “x”.

$$A = f(L, \dots)$$

- The third relation is between the ratio “ L/H ” and the parameter “A”.

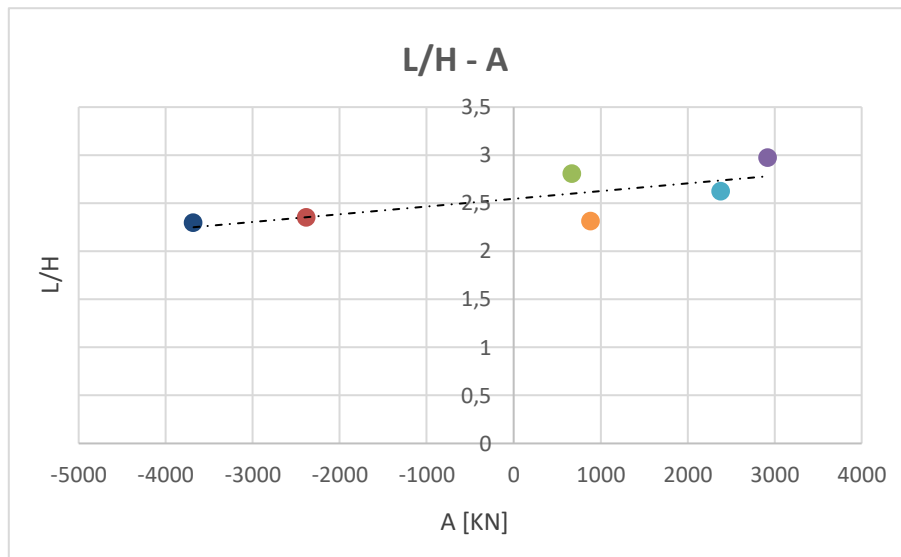


Figure 3.14 Relation between the parameter “A” and ratio “ L/H ”.

As can be seen in Figure 3.14 the relation between “A” and “ L/H ” shows an upward trend. With small changes in the ratio, a big increase of the parameter “A” takes place. The smaller the ratio, the smaller the tensile stress value. For instance, the green point corresponds to the M30 Tunnel in Madrid whose diameter is larger than the one in Sants-Sagrera tunnel (yellow point). However in the graph, can be appreciated that with a smaller ratio “ L/H ” the tensions are significantly lower.

$$A = f(L, L/H, \dots)$$

Segment damage

Once the main tensile stresses for the uneven support case 1 are identified, the most likely failure patterns are presented. The failures in the segment can be divided into two kinds. The first one is the cracking due to high tensile stresses and the second one is the punctual failure in the edges of the segment.

In the uneven support case 1, the main tensile stresses due to the hydraulic jack's pressure are developed in the middle upper part of the segment between the bearing pads. As a result, a longitudinal crack may occur as it is shown in Figure 3.15.

The edges of the segments are very vulnerable to high forces. A big compression takes place and produces an extraction of the segment's edge. In this case, only the upper left edge of the segment "j + 1" may be exposed to such conditions. As a result, a punctual failure may take place as it is shown in Figure 3.15.

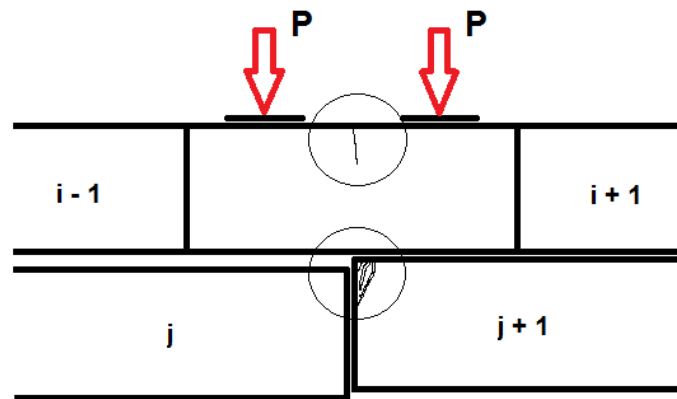


Figure 3.15 Segment damage

3.2.2 Case 2 Positive turn of the support segment and negative turn of the analysed segment

In the analysis of the second case it is appropriate to make the difference between the two load situations mentioned before, as the stress field can considerably change due to the different support conditions. The first case Figure 3.16(a) is when the segment "i + 1" is not installed yet and the second case Figure 3.16(b) is when the whole ring is placed and the hydraulic jacks push forward the shield.

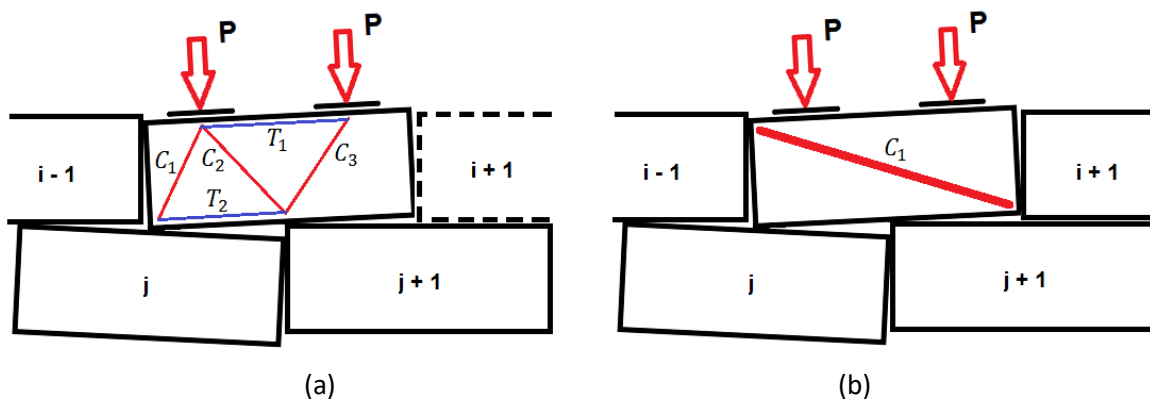


Figure 3.16 Main stress fields according to different support conditions.

In both subcases, the uneven support is due to a turn in the segment "j" (see Figure 3.16). This irregularity can lead to a situation that can be approximated as in case 1. The pressure P is equal in both jacks and the segment "i + 1" is not installed yet. As a theoretical situation, the horizontal reaction in the contact point in the upper left side of the segment can be assimilated as very small or even zero (See Figure 3.16 (a)).

However, when the segment “ $i + 1$ ” is already placed, the situation changes as another horizontal reaction in the lower right side of the segment occurs. The worst situation in this case would be an ideal situation where there is no contact with the previous ring and all the pressure coming from the jacks would be transmitted to the lateral supports.

Even though this situation is not truly possible, it can happen that the force transmitted to the supports in the lower part of the segment are very small due to the friction force in the longitudinal joints. Because of that, the situation analysed in this section is the ideal situation, which consists in no lower supports as it is represented in Figure 3.17.

Geometry of the segment “ i ”

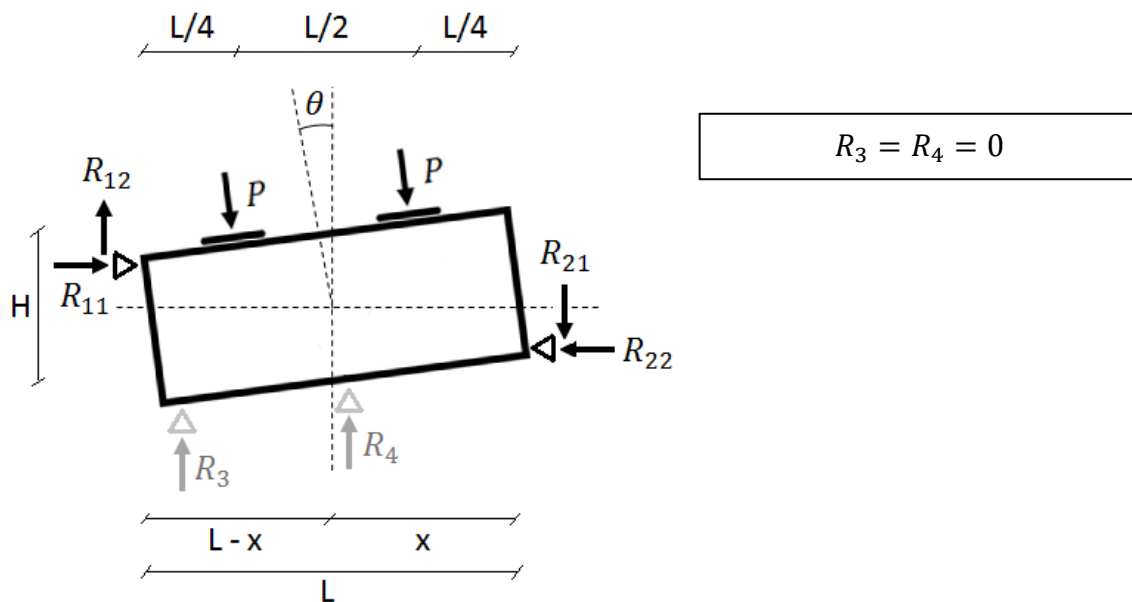


Figure 3.17 Geometric parameters of segment “ i ” and values of the vertical reactions.

Segment damage

In this particular case, the main stress field in the segment is a compression strut going from one lateral support to the other as it is shown in Figure 3.16 (b). As concrete works well under compression stresses, the most critical situation for the segment is in the lateral supports, where a punctual failure may occur due to the high force applied.

In Figure 3.18 the punctual failure in the lateral edges of the segment is represented. In this case, a piece of the segment’s corner may break. The segment’s broken piece is triangularly shaped and depends on the direction of the force applied as it can be seen in Figure 3.18.

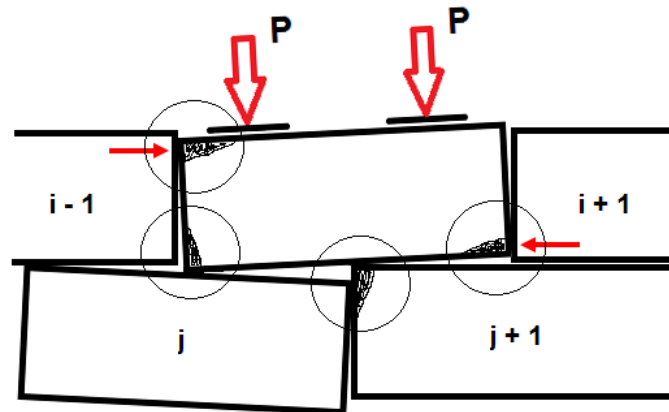


Figure 3.18 Punctual failure in the lateral and middle supports of the segment.

3.2.3 Case 3 Rotation of segments “j” and “j+1”

In the third case, the uneven support is due to a rotation of the segments of the previous installed ring as it is shown in Figure 3.19. A positive turn of segment “j” and a negative turn of segment “j + 1” enables segment “i” to sink.

In this case, the worst scenario is when the segment “i + 1” is not installed yet. The reason is, if there were segment “i + 1” installed, part of the force applied would dissipate in the longitudinal joints and the force transmitted to the supports in the lower part of the segment would be smaller. Therefore, the following case analysed is when the segment is loaded, in order to keep it in place while the rest of the segments of the ring are installed.

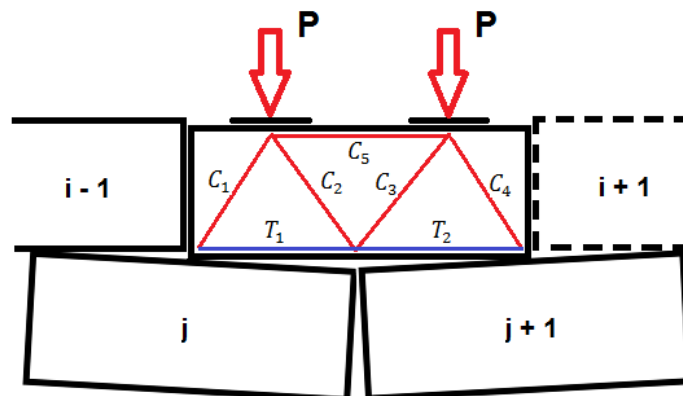


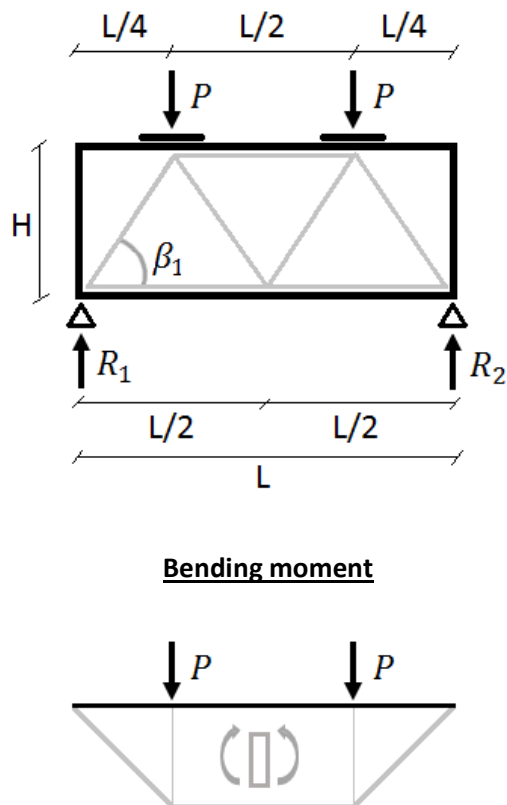
Figure 3.19 Strut-and-tie model for case 3.

As in some of the previous cases, the friction of the longitudinal joints is not taken into account. This means that all the force from the hydraulic jacks is transmitted to the supports in the contact area of the circumferential joint. In this scenario, the supports are in the edges of the segment and an opening in the longitudinal joint may occur.

In order to analyse more carefully the situation in the uneven support case 3, the geometric parameters and the support conditions of the segment are shown in Figure 3.20. The

stresses developed in the segment are calculated through a Strut-and-tie model shown in Figure 3.19.

Geometry of the segment "i"



Equilibrium equations

$$\beta_1 = \tan^{-1} \left(\frac{H}{L/4} \right)$$

$$R_1 = R_2 = P$$

(1)

Maximal Bending moment

$$M_{max} = P \cdot \frac{L}{4}$$

Compatibility equation

$$\varepsilon_c = \varepsilon_s \quad (2)$$

Figure 3.20 Geometry of segment "i" and bending moment's diagram with equilibrium equations, maximal bending moment and compatibility equation.

Calculation of the stresses through the strut-and-tie method

In accordance with the equilibrium equations (1) and the compatibility equation of strain (2), the following relations are presented:

$$T_1 = C_1 \cdot \cos \beta_1 \quad (3.6)$$

$$P = C_1 \cdot \sin \beta_1 \rightarrow C_1 = \frac{P}{\sin \beta_1} \quad (3.7)$$

$$T_1 = P \cdot \frac{\cos \beta_1}{\sin \beta_1} = P \cdot \cot \beta_1 \quad (3.8)$$

The value of T_1 depends only on the segment's geometry and the value of P . The eccentricity of the longitudinal joint of the previous ring doesn't play a significant role in this case. Both supports are placed in one edge of the segment and the stress distribution throughout the segment can be considered as symmetric. In case that the longitudinal joint was

shifted from the middle point of the segment, a turn of the segment “i” might occur and the effect of lateral supports wouldn’t be negligible.

In the analysis of this case it is reasonable to consider the bending moment diagram in order to determine the most likely area to be cracked. In the Bending moment diagram, it is shown that the segment is submitted to both pure bending in the central part of the segment and simple bending in the parts close to the supports. Therefore, the most vulnerable area to failure is the area where there is an abrupt change of the stresses.

A more detailed analysis of the stresses developed in the segments is done, particularly for the tensile stress T_1 . As it is mentioned above, T_1 only depends on the segment’s geometry. That is why, an analysis of the same particular cases as in case 1 is carried out.

Particular cases and comparison

The following data of real tunnels in Table 3.4 are considered to analyse the relationship between the tensions developed in the segment and the segment’s geometry in this case of uneven support. The tension T_1 is calculated through the following equation.

- Equation of T_1

$$T_1 = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{L/4} \right) \right) \quad (3.9)$$

- Data of existing tunnels

Table 3.4 Existing tunnels data. (Ainchil)

Tunnel	P [KN]	H [mm]	L [mm]	L/H	T_1 [KN]	\emptyset [mm]
Fontsanta-Trinitat	6500	1400	3210	2,29	3725,89	5200
Metrorex Boltari	6500	1500	3534	2,36	3828,50	5700
Middle East Metro Line	6500	1600	4489	2,81	4559,14	8700
Sants-Sagrera	6500	1800	5347	2,97	4827,15	10400
Ave Trinitat-Montcada	6500	2000	5244	2,62	4260,75	10400
M30 Madrid	6500	2000	4631	2,32	3762,69	13450

- Plot

With the previous data, the relationship between T_1 and " L/H " is plotted.

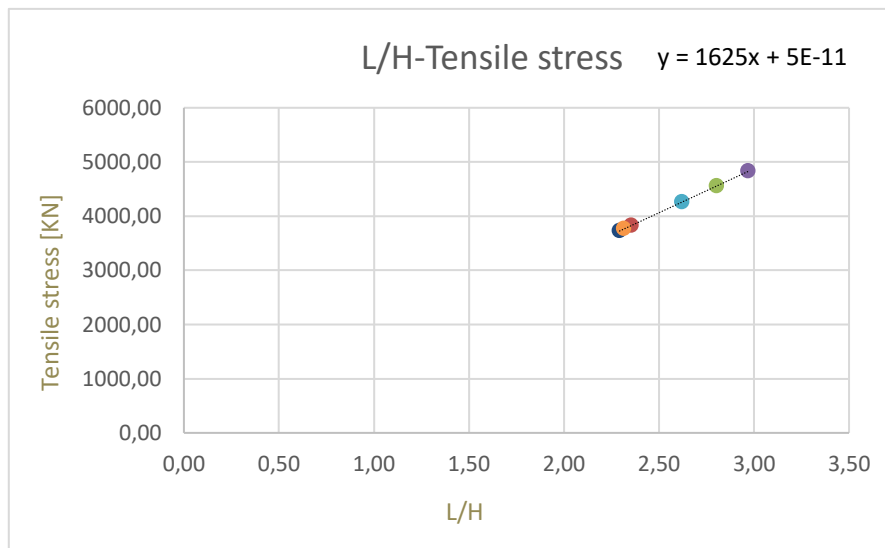


Figure 3.21 Relation between " L/H " ratio and the tensile stress T_1 .

As in this case it is considered that the situation is symmetric, the eccentricity of the longitudinal joint is not taken into account. If the longitudinal joint were displaced to one side, a turn of the segment would take place and some of the force would dissipate in the lateral supports. That is why, the worst scenario is when the longitudinal joint is in the middle and all the force is transmitted to the supports in the edges.

As can be seen in Figure 3.21, there is a linear relation between the tensile stress T_1 and the ratio between segment's length " L " and width " H ". The bigger the " L/H " ratio, the higher the tensile stresses developed in the lower part of the segment. In this case of uneven support, an approximation of the value of the tensile stress T_1 can be calculated with the following formula obtained from the graph in Figure 3.21.

$$T_1(x) = 1625x - 2 \cdot 10^{-9} \cong T_1(x) = 1625x \quad (3.10)$$

$$T_1 = f(L/H)$$

Segment damage

In this case of uneven support, the segment undergoes a bending moment due to its support conditions. That is why this case can be assimilated to a tested beam in a flexion test. The higher tensile stresses are in the lower part of the segment and as a result longitudinal cracks as the ones shown in Figure 3.22 may occur.

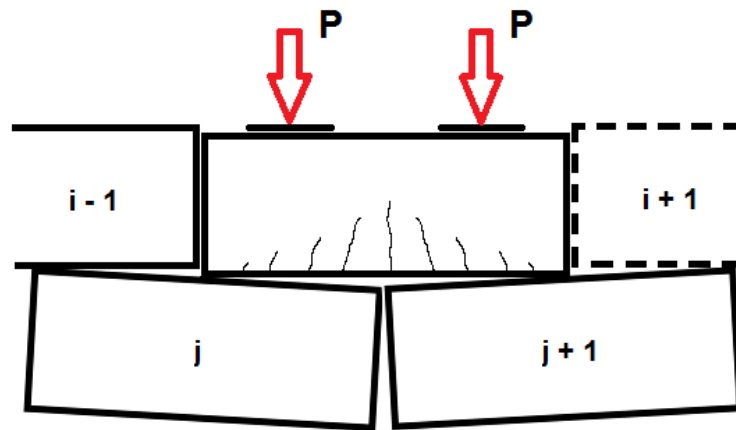


Figure 3.22 Segment damage case 3.

3.2.4 Case 4 Rotation of segments “j” and “j+1”

In the fourth case, the uneven support is due to a rotation of the segments of the previous installed ring as it is shown in Figure 3.23. A positive turn of segment “j + 1” and a negative turn of segment “j” enables segment “i” to go upwards.

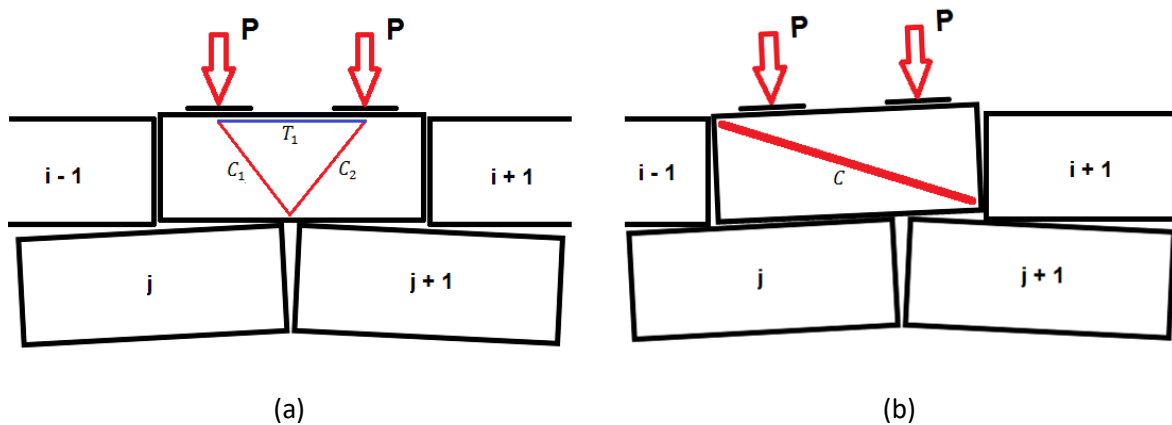


Figure 3.23 Strut-and-tie models for case 4.

In this case, there are several possible scenarios that can occur in reality and lead to the development of high stresses in the segment. First of all, let's assume that both P 's are equal, however, it is known that it is not always this way. As it is mentioned in the previous cases, the two main loading situations are with and without segment “i + 1” corresponding to the advance of the TBM and the moment when the rest of the segments of a ring are installed respectively. However, in this case, only the loading situation of the advance of the machine is considered as the worst scenario.

Case 4 is analysed by making the difference between two situations. The first situation considers that the irregularity of the longitudinal joint is exactly in the middle of the segment “i” Figure 3.23(a) and the second situation considers an eccentricity of the longitudinal joint as shown in Figure 3.23(b).

As in this chapter the influence of the longitudinal joints is not considered, in the first situation (a) there is no theoretical difference between the situation with and without segment “i + 1”.

In order to proceed with a more detailed analysis of the case, the segment geometry is presented in Figure 3.24. As follows, the calculation of the tensile stress T_1 through the Strut-and-tie model is carried out.

Geometry of the segment i

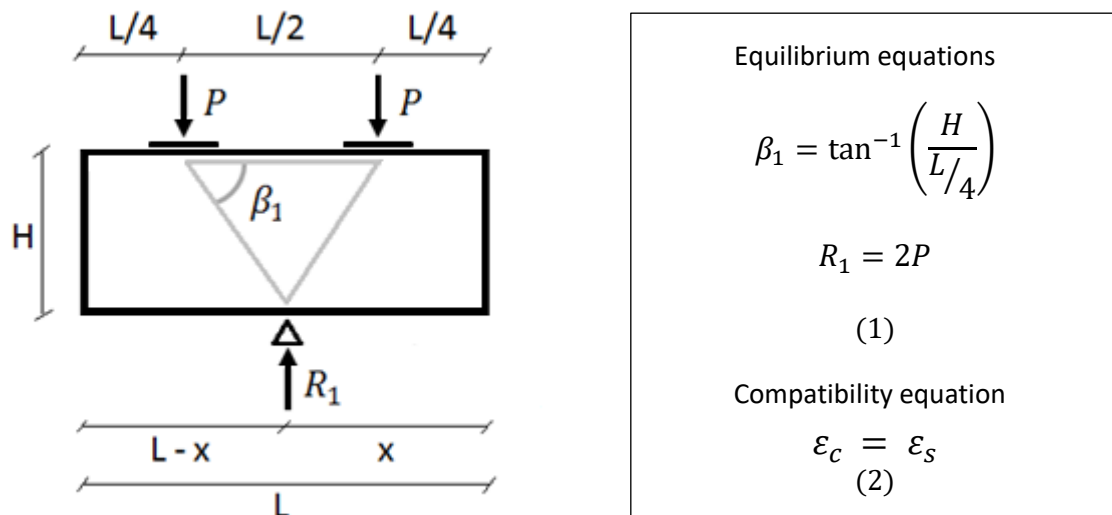


Figure 3.24 Segment “i” geometry, equilibrium equations and compatibility equation.

Calculation of the stresses through the strut-and-tie method

In accordance with the equilibrium equations (1) and the compatibility equation of strain (2), the following relations are presented:

$$T_1 = C_1 \cdot \cos \beta_1 \quad (3.11)$$

$$P = C_1 \cdot \sin \beta_1 \rightarrow C_1 = \frac{P}{\sin \beta_1} \quad (3.12)$$

$$T_1 = P \cdot \frac{\cos \beta_1}{\sin \beta_1} = P \cdot \cot \beta_1 \quad (3.13)$$

In this case, the formula of the tensile stress T_1 is the same as in case 3 and the position of them in the upper middle part of the segment as in case 1. However, in case 3 the tensions are in the lower part of the segment. The difference with case 1 remains in the compression struts, as in case 4 there are only two. This means that the values of these compression struts in this case will be larger.

- Equation of T_1

$$T_1 = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{L/4} \right) \right) \quad (3.14)$$

Segment damage

In case 4, it is worth to analyse the two situations shown in Figure 20. The first situation (a) takes place when the longitudinal joint of the adjoining ring is placed right in the middle of the segment. The second situation (b) takes place when the longitudinal joint is displaced to one side (See Figure 3.25).

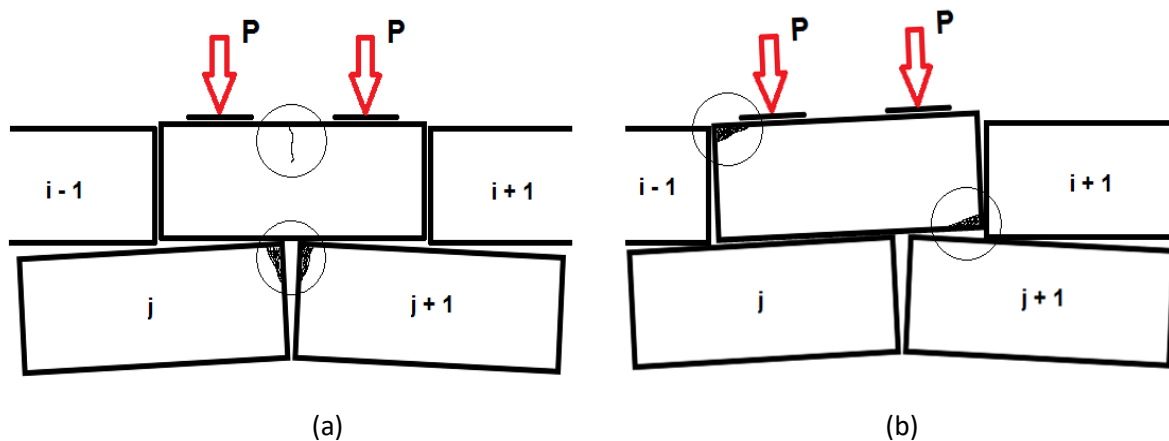


Figure 3.25 Segment damage case 4

- Situation (a)

In this situation, two kinds of failures are likely to occur. The first one is the longitudinal cracks in the middle upper part of the segment due to the high tensile stresses developed. The second one is the punctual failures on the edges of segment “j” and “j + 1”. In this case, as there is only one support available where the forces can be transmitted, the compression in the support will be higher. As a result, a high compression on the corners of the segments “j” and “j + 1” takes place. This high compression may lead the corners to break as it is shown in Figure 3.25(a).

- Situation (b)

Situation (b) is slightly different as the displacement of the longitudinal joint of the adjoining ring leads to a turn of the segment “i”. In this case, as in case 2, a big compression strut takes place. It is necessary to consider the effect of the longitudinal joints of segment “i” as two more supports where the forces will be also transmitted appear. This high compression of the lateral supports of the segment can lead to punctual failures on the corners of segment “i” as it is shown in Figure 3.25 (b).

4. RADIAL ECCENTRICITY OF THE HYDRAULIC JACKS

4.1 INTRODUCTION

Tunnelling machines are multidisciplinary machines that build the lining of the tunnel at the same time that excavate the front. To do so, they make use of hydraulic jacks supported in the already installed rings to push forward the cutter head. The connection between the two simultaneous procedures are the hydraulic jacks.

While the cutter head excavates, the hydraulic jacks provide the necessary pushing force to go ahead by supporting themselves in the last installed ring. As a result of this pushing force, stresses are developed in the segments and failure may occur.

A possible cause of failure is directly related to the hydraulic jacks and how they apply the force in the lining. Generally, in the most recent projects, the force transmission is carried out by two or three pairs of hydraulic cylinders per segment. However, in the presented paper only two pairs of hydraulic jacks are considered. In this chapter, the important issue is the way cylinders transmit the force to the segment. This transmission is by means of a flat support linked to the cylinders equipped with bearing pads. In Figure 4.1 the shoe of the cylinders is shown, they have a rectangular shape that fits in the thickness of the segment.

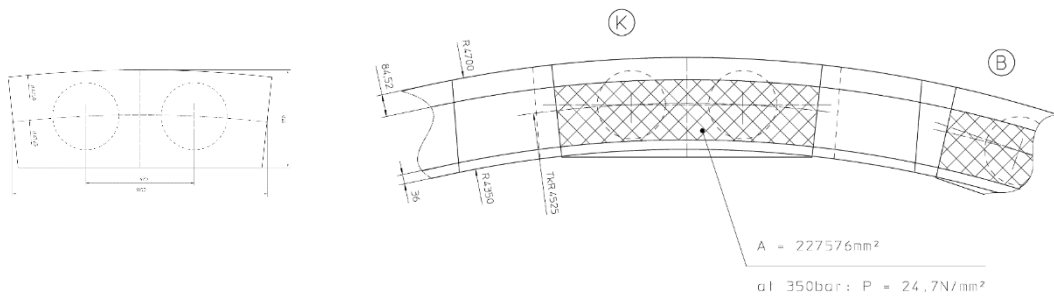


Figure 4.1 Shoe's geometry of a pair of hydraulic jacks supported in a segment. (Middle east metro line)

These shoes are designed so that they fit correctly in the segment with a certain radial eccentricity of design in order to provide more stability to the segments. However, in reality, the deviation of this eccentricity can be larger than that due to several reasons. The radial eccentricity "e" is represented in Figure 4.2. The main reasons are related to the TBM steering and the curve actuation.

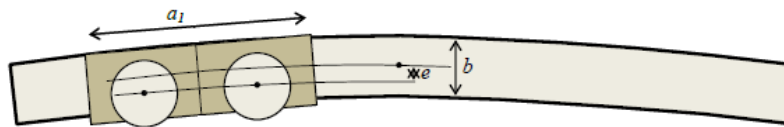


Figure 4.2 Radial eccentricity "e". (Carbonari 2011)

As previously mentioned, the hydraulic jacks do not apply the same pressure all around the ring. In order to turn or to keep the TBM face in a straightened position, the pressure is non-uniformly distributed around the ring. Due to the unbalance of the pressure, the pads may not actuate in the most optimal position. An example of this improper position can be observed in Figure 4.3 which corresponds to a segment of the L9 metro line in Barcelona.



Figure 4.3 Radial eccentricity of hydraulic jacks in the L9 metro line in Barcelona.

The study of the stresses developed in the segments is carried out by means of the so-called Strut-and-tie method as done in the previous chapter. The aim of using this method is to acquire a more physically visible approach to the stresses developed in the segments during the construction stage.

Analysis of the damage in precast concrete tunnel segments during construction phase and the influence of FRC

This kind of irregularity occurs often in the construction site and can be the reason of a loss of quality in the lining. That is why, the radial eccentricity of the hydraulic jack's shoe and the stresses developed in the segment are analysed more carefully in the following sections.

4.2 STRESS DEVELOPMENT AND CRACK PATTERNS

The next step is to understand and identify the stresses developed in the segment due to the point load applied by the hydraulic jacks and its eccentricity. To follow with the same steps as in the previous chapters, the analysis of the stresses is carried out by means of a simplified Strut-and-tie model. Once the stress fields in the segment due to a point load are identified, the effect of the eccentricity is easier to understand.

In Figure 4.4(a) the strut-and-tie model for the segment is shown. The figure represents a transversal cut of the segment in the middle part of the hydraulic jack's shoe. Discontinuous lines represent the compression struts and straight lines represent the tension ties. In Figure 4.4 (b) the variation of the stresses along the segment is presented. The stress field developed in the segment can be assimilated to the one in a solid block member under a concentrated load. In Figure 4.4 (c) the shape of the stress field when the pressure of the hydraulic jacks is applied with a certain eccentricity " ε_r " is presented. As it is shown, the stress field is shifted closer to the edge of the segment what will bring decisive consequences to the punctual failure of the segment edge.

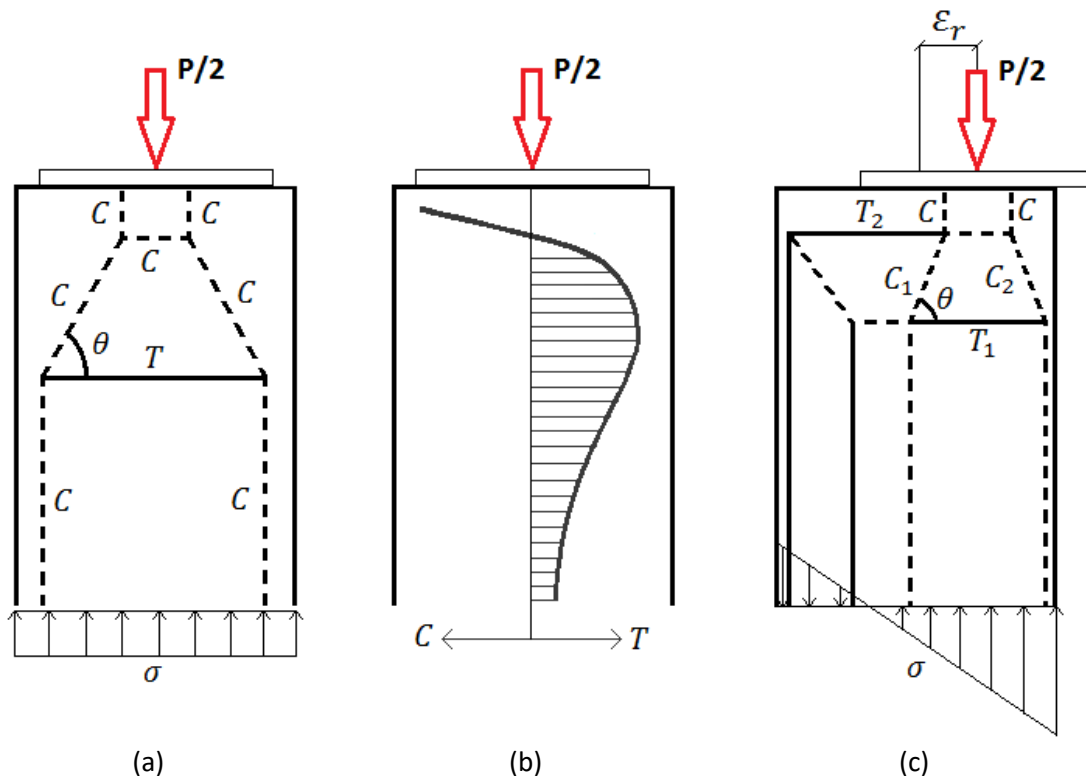


Figure 4.4 Representation of the stress field in a transversal cut of the segment through a strut-and-tie model (a). Variation of the stresses along the segment depth without eccentricity (b). Stress field regarding radial eccentricity " ε_r " (c).

In terms of analysing the effect of the pressure done by the hydraulic jacks, it is interesting to go deeper into the stress field developed right under the bearing pads, or better said under the point load applied by the hydraulic jacks. In this area, a multiaxial compression field occurs.

According to Leonhardt (1965), the external force P is expanded through the structure the way that originates a stress field of principal stresses with tension and compression components which are transversal to the external force applied. These stresses are expanded until a certain length of penetration where the distribution becomes uniform. This area of penetration is also called St Venant zone, where the stresses cannot be calculated through the common flexion theory.

The loading case of the segments can be assimilated to the stress field developed in a concrete specimen in a *compressive strength test* or in an *indirect tensile strength test* which can help to identify the kind of failure that may occur in reality due to the pushing pressure of the jacks.

In this section, both tests are presented and associated to the stress field developed in the precast concrete segments. The aim of it is to find a reliable explanation to the stress field's behaviour and failure causes due to the hydraulic jack's pressure and subsequently its radial eccentricity.

Compressive strength test

The first case corresponds to the compressive strength test which is one of the most common tests that are carried out to determine the properties of the hardened concrete. The test consists in measuring the compressive strength of the hardened concrete by breaking cylindrical or cubic specimens with a compression-testing machine.

However, in this section, what is more important is how the stresses are developed along the specimen and the crack pattern of the breaking. This will help to assimilate the loading case of the specimens to the one in the segments under the load of the hydraulic jacks.

In a compression test, a multiaxial compression stress field is developed close to the upper and lower edge of the specimen. Due to friction, the way cracks spread throughout the specimen during failure generates a typically conical shaped fracture on the upper and lower edges with high tensile stresses in the middle of the specimen as shown in figure 4.5 (b).

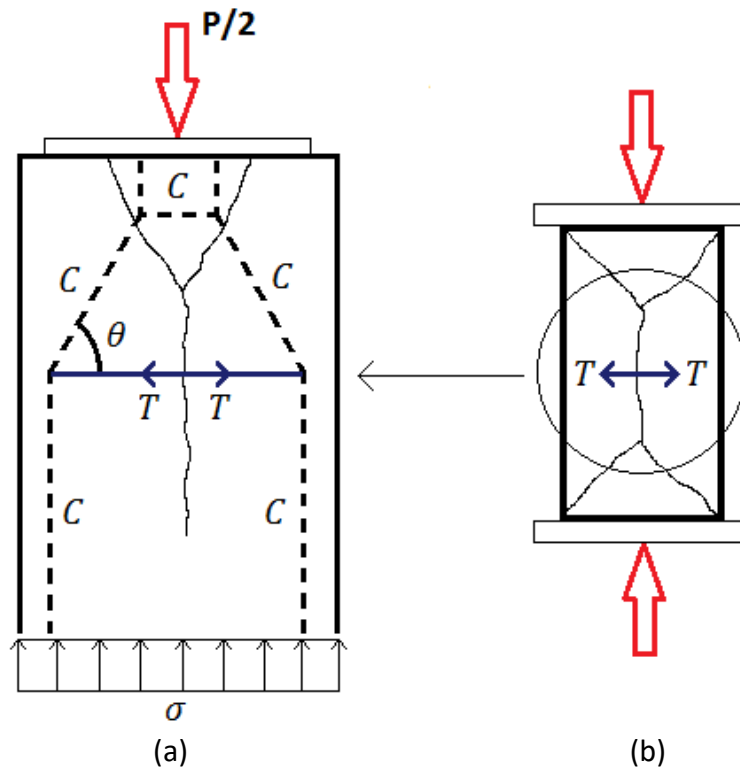


Figure 4.5 Strut-and-tie model for the area under the bearing pads (a).
Typical conic shaped fracture in a compression test. (b)

The high tensile stresses developed in the middle part of the specimen lead to longitudinal cracks. This scenario can be assimilated to the loading case of the segments where high tensile stresses are developed under the bearing pads. These tensile stresses can lead to longitudinal cracks following the failure pattern of the specimens tested in a compressive strength test.

Indirect tensile strength test (Brazilian test)

Concrete is a brittle material and it is easily cracked when subjected to tensile stresses. That is why, the determination of concrete's tensile strength is important. As direct tensile stress tests are difficult to perform, the indirect tensile stress test, also called Brazilian test or diametral compression test, was developed.

The Brazilian test consists in compressing cylindrical specimens horizontally placed by means of a compression machine as it is shown in Figure 4.6 (b). Around 75% of the specimen is subjected to tensile stresses as it is shown in the distribution of horizontal stresses in Figure 4.6 (c) Due to the tensile stresses developed in the specimen, it breaks with a sudden and violent failure when the peak load is reached.

The stresses developed in the tested specimens in a Brazilian test can be also assimilated to the stresses developed in the segments during the construction stage as it is shown in Figure 4.6(a). The hydraulic jacks press the segments and bursting stresses occur under the bearing pads which can lead to cracks in the longitudinal direction.

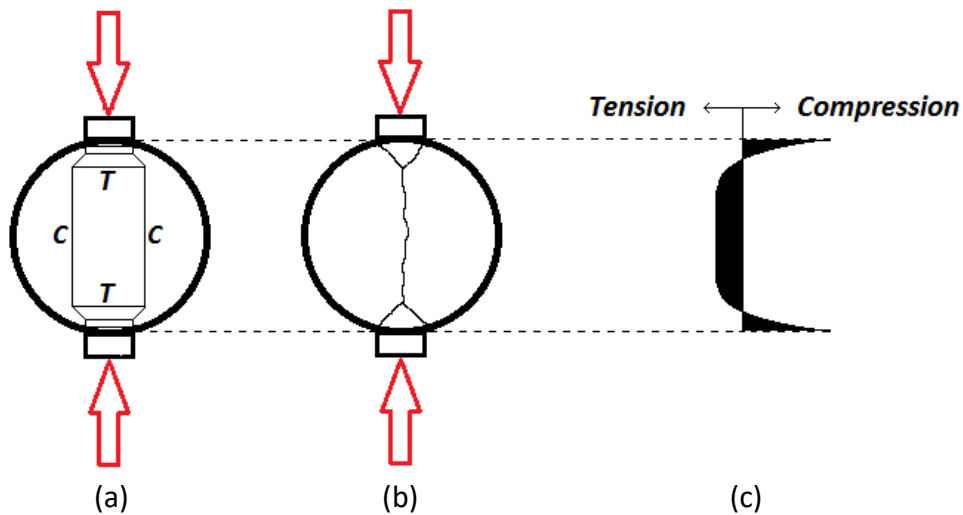


Figure 4.6 Strut-and-tie model for a specimen in a diametral compression test (a). Diametral compression of a cylindric specimen (b). Distribution of horizontal stresses (c). (Carmona and Aguado 2012)

In the following sections, the effect of a concentrated load in a solid block member and the effect of the radial eccentricity are presented.

4.3 SOLID BLOCK MEMBER UNDER CONCENTRATED LOAD

This loading case leads to the appearance of longitudinal cracks due to the tensile stresses developed in the middle part of the segment. As shown in the previous section, the stress field in the segment is the one of Figure 4.7. The crack pattern can be assimilated to the one in the compressive strength test or in the indirect tensile stress test.

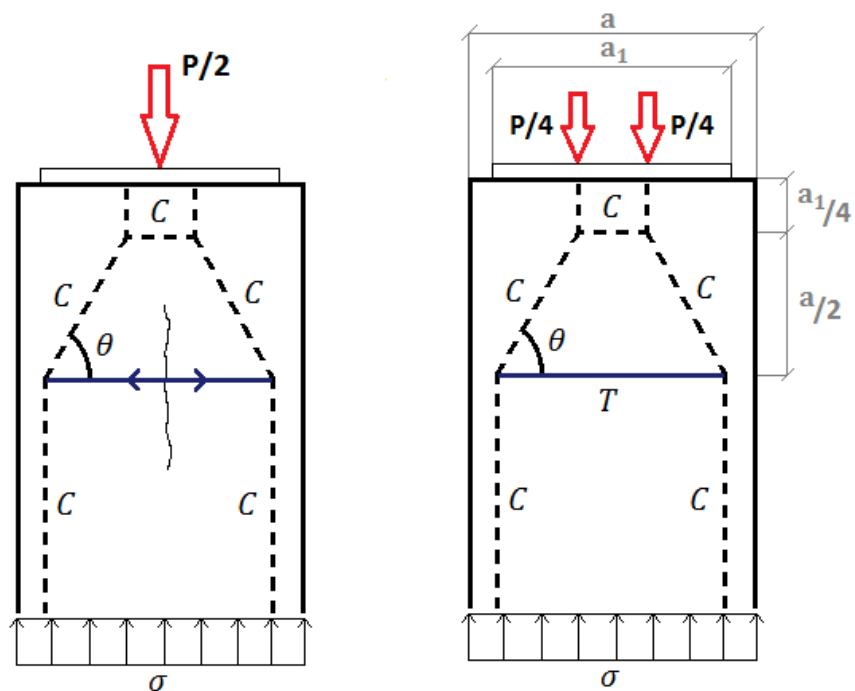


Figure 4.7 Longitudinal crack in the segment due to a concentrated load. Compressive strength test.

The calculation of the stresses is carried out by means of the formula presented in the EHE-08 and Leonhardt (1964) for a block member under a concentrated load. The geometry of the segment is presented in Figure 4.7. The formula includes the parameters a_1 which is the length of the hydraulic jack's shoe.

$$T = 0,25 \cdot N_d \cdot \left(\frac{a - a_1}{a}\right) \tag{4.1}$$

$$N_d = P/2 \tag{4.2}$$

4.4 EFFECT OF RADIAL ECCENTRICITY “ ϵ_r ”

In the previous section, the stress field developed in the segment due to the hydraulic jack's force is characterized through the so-called Strut-and-tie method. Once the stress field is known, what is more interesting is to identify how this stress field varies because of the radial eccentricity of the force.

As can be seen in Figure 4.8 the whole stress field is shifted to the edge of the segment. A multiaxial compression field is developed right under the bearing pad. Deeper in the segment, tensile stresses transversal to the force applied occur. This concentration of stresses on the edge of the segment can lead to the fracture of a piece of the segment's edge. As follows, a more detailed analysis of the failure situation is presented.

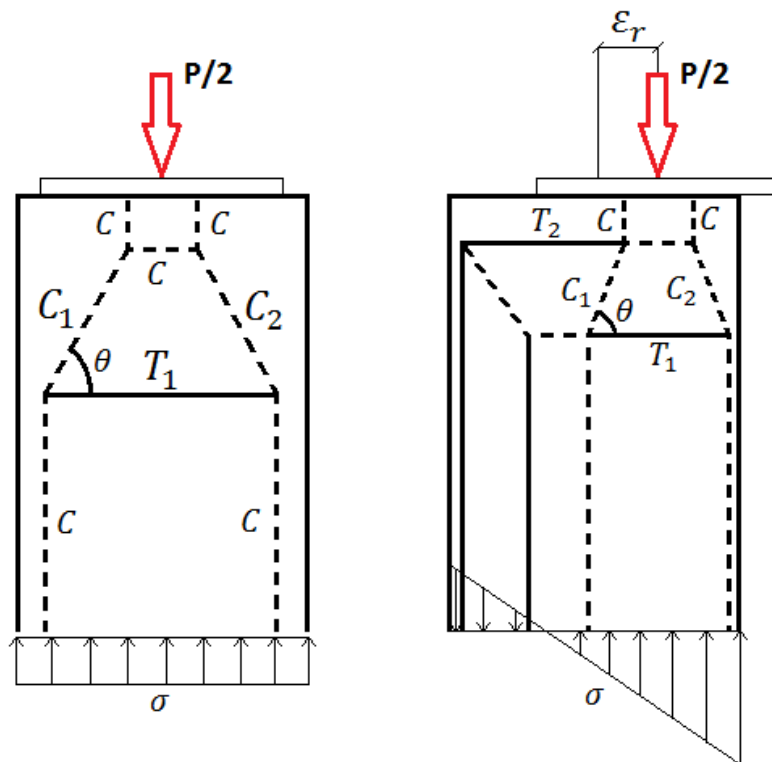


Figure 4.8 Effect of radial eccentricity in the stress field of the segment

Fracture of an edge's piece

The concentration of compressive stresses close to the edge of the segment can lead to a local shear failure. This kind of failure is similar to the one in the upper part of the specimen in the indirect tensile stress test. This kind of failure is a shear failure and has a tapered shape as can be seen in Figure 4.9.

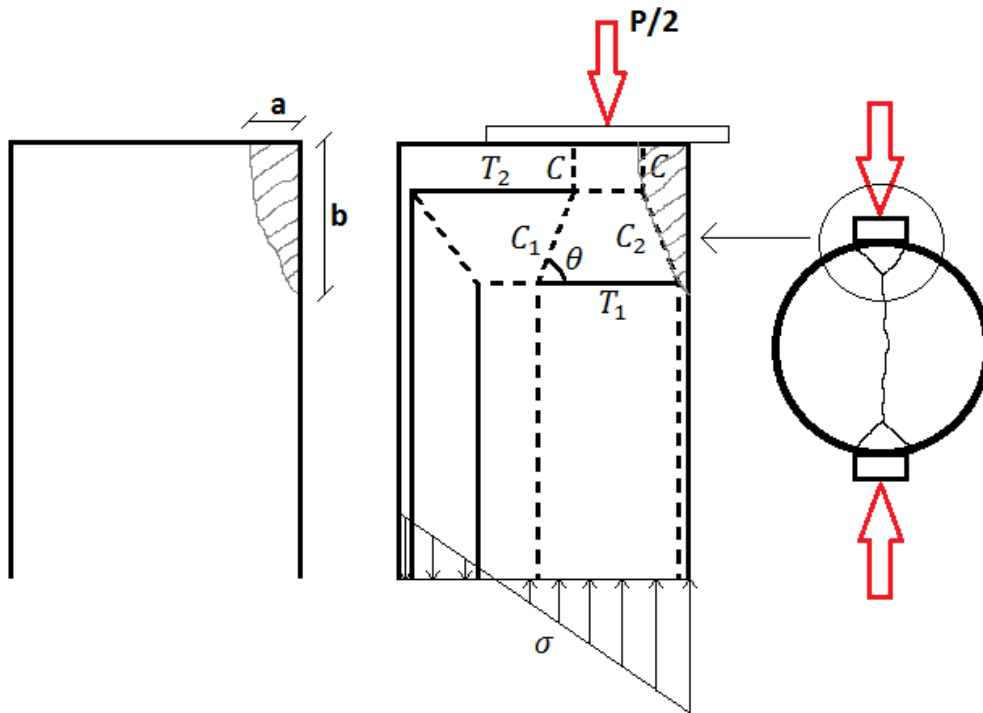


Figure 4.9 Fracture of an edge's piece and indirect tensile stress test specimen crack pattern. Geometry of the fractured piece.

In this case, the compressive stress that must be resisted in the segment is C_2 . The geometry of the fractured piece is approximated to a triangle as shown in Figure 4.10. The value of C_2 is calculated according to the approximate geometry of the fractured piece and considering that the fracture forms and angle α as shown in Figure 4.10. Figure 4.10 represents a sketch of the segment and the position of the hydraulic jack's shoe with the corresponding type of failure due to the radial eccentricity.

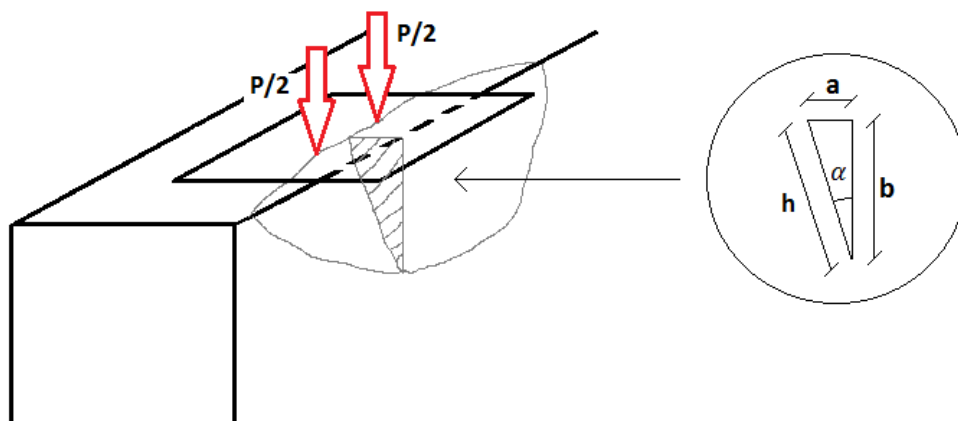


Figure 4.10 Sketch of the fractured piece and its geometry parameters.

As follows the value of the compression strut C_2 is presented according to the assumptions presented above:

$$C_2 = \frac{P}{2} \cdot \frac{1}{\cos \alpha} \quad (4.3)$$

This variation can lead to two kinds of failure. A structural one, a little under the point of application of the load in terms of longitudinal cracks and a punctual one, right on the edge of the segment in terms of detachment of a concrete piece.

In the first case, the type of loading case can be assimilated to a concentrated load under a solid member. As it is explained in the corresponding section and according to the strut-and-tie model exposed, the segment develops high tensile stresses in the area a little under the bearing pads. This tensile stresses may lead to longitudinal cracks as it is shown in Figure 4.7.

The second case consists of a localized fracture of the concrete due to the excessive radial eccentricity of the hydraulic jack's. If the pressure is very high and goes together with an excessive radial eccentricity, compressive stresses will be concentrated close to the edge of the segment. This concentration of stresses may lead to a shear stress failure, overcoming the shear resistance of the concrete, which without any type of reinforcement may crack.

5. STEEL FIBRES IN PRECAST CONCRETE SEGMENTS

5.1 INTRODUCTION

The precast concrete segments used in the construction of tunnel linings are usually reinforced with conventional rebar. However, the appearance of cracks and other kind of failures in multiple real cases has induced to rethink the type of reinforcement. One of the considered solutions is the introduction of fibres in the concrete matrix.

The aim of this chapter is to describe the improvements of the introduction of the fibres in the concrete and identify its advantages regarding the failure cases described in the previous chapters. A brief overview of the mechanical properties and the constitutive models according to the EHE-08 used for the design of fibre reinforced concrete members is given. Furthermore, a practical example for each type of segment failure studied in the present study is carried out. The practical example corresponds to the Trinitat-Fontsana tunnel of water conduction.

According to the EHE-08, fibre reinforced concrete (FRC) can be defined as concrete with discrete short fibres randomly distributed in its mass. The FRC can be used for structural and non-structural purposes. For structural purposes, the steel fibres are the most commonly used (SFRC). In the cases where the fibres have a structural role, their contribution is taken into account in the calculations of the ultimate or serviceability limit states where they can partially or totally replace the conventional reinforcement. If the fibres have a non-structural role but the aim of improving certain properties such the increase of fire resistance, control of shrinkage

cracking, abrasion, impact among others, their contribution will not be considered in the calculation. In the following diagram, the classification of the fibres according to the Spanish regulation EHE-08 is shown (See Figure 5.1).

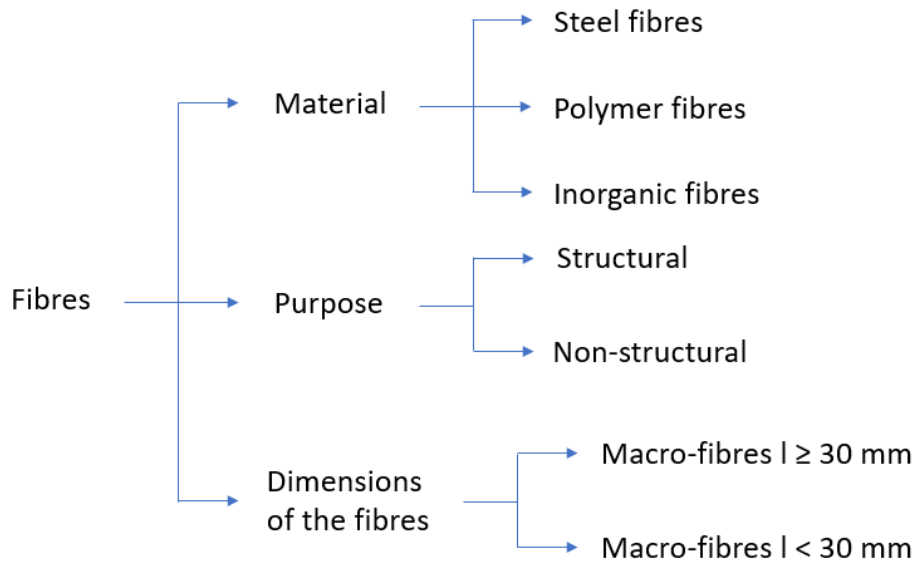


Figure 5.1 Type of fibres according to the EHE-08. (EHE-08 2008)

The geometric characteristics and the shape of the fibres are very important in terms of the bonding characteristics of the fibres with the concrete and may be very varied: straight, undulated, corrugated, shaped with different-shaped ends, etc. The geometric characteristics of the fibres are the ones presented below and are established in accordance with the UNE 83500 Part 1 and UNE 83500 Part 2:

Length l_f	Equivalent diameter d_f	Slenderness $\lambda = l/d$
--------------	---------------------------	-----------------------------

According to the EHE-08, the following recommendations for the geometric characteristics of the fibres are presented. The length of the fibre should be at least twice the size of the largest aggregate. The commonly used lengths range is between 2,3 and 3 times the maximum aggregate size. If the FRC is pumped in pipes, the length of the fibres must be less than two thirds of the pipe diameter. However, the fibre length must be long enough to ensure the bond with the matrix and to prevent pull-out occurring too easily.

In order to densify the mesh of fibres, fibres of equal length and smaller diameter are used as the number of them per unit weight will increase. Fine Fibres are more suitable as the space between them is reduced and as a result an improvement of the redistribution of the load or stresses occurs.

In terms of structural purposes, the higher the ratio between the length and the diameter of the fibre (slenderness), the higher is the performance of the FRC. However, if the slenderness is too high, concrete may have workability problems.

In the dosage of a FRC the following parameters need to be specified:

- The dosage of fibres in Kg/m^3
- If the fibres have a structural purpose, the specification of the type, dimensions (length, effective diameter and slenderness), shape and tensile strength of the fibre are required.

Fibre reinforced concrete contribute in many aspects in the fabrication of precast tunnel segments. The addition of fibres in the concrete contributes to the improvement of the structural behaviour, the durability and can in some stages reduce the costs. The conventional reinforcement has some problems that are tried to be mitigated with the addition of fibres. For instance, the lack of reinforcement on the segment edges. In Table 5.1 the advantages of the FRC are compiled.

Table 5.1 Advantages of FRC.

Structural contribution	Durability	Cost savings
Increase of crack control and bearing capacity	Fire resistance Better performance in elevated temperatures	Reduce amount of steel
Increase of toughness and ductility	Increase of impact and fatigue resistance	Smaller storage area
Smaller crack widths	Less corrosion and abrasion	Less working operators and shorter times

Structural contribution

Concrete is a brittle material and its tensile stress resistance is approximately 10% of its compressive stress resistance. Therefore, the introduction of reinforcement is required. The reinforcement improves the behaviour of the composite material under tensile stresses and avoids its failure. Since some years ago, other types of reinforcement apart from the conventional rebar have been investigated in order to improve some of the concrete characteristics.

In this paper, the reinforcement alternative presented is the steel fibres. As can be seen in Figure 5.2, the bearing capacity of the fibre reinforced concrete is higher than the one of mass concrete but lower than the one of conventional reinforced concrete. That is why, in some cases the combination of both is an optimal solution.

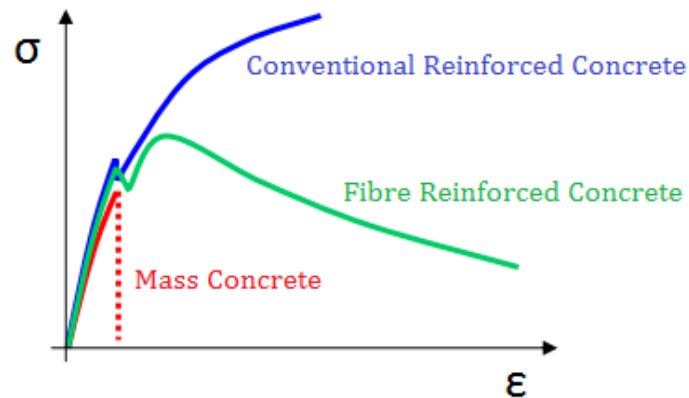


Figure 5.2 Stress-strain relationship of three types of concrete

As can be seen in Figure 5.3, the introduction of fibres in the concrete increases substantially its ductility. The fact that the fibres are randomly distributed, enables a better crack control and the ability to hold the matrix together. In addition, the stress distribution after cracking is improved what results in smaller crack widths. In Figure 5.3 the comparison of the behaviour of the conventional reinforcement and the fibres reinforcement under tensile stresses is presented.

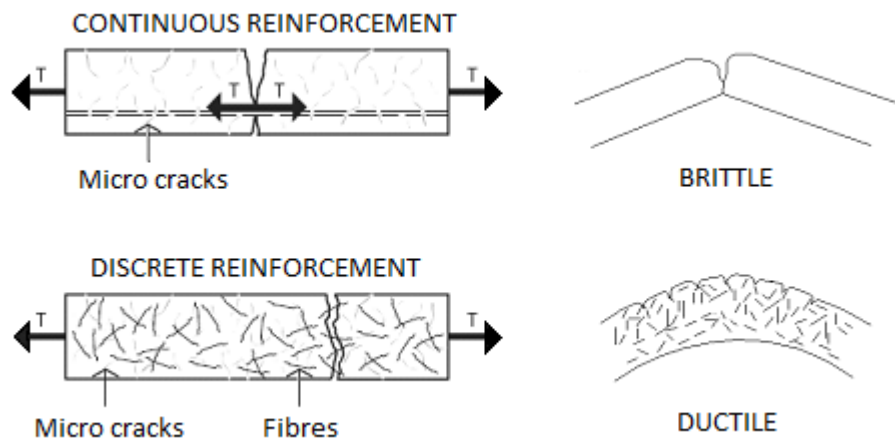


Figure 5.3 Behaviour of conventional reinforced concrete and fibres reinforced concrete under tensile stresses and comparison of ductility.
(<http://www.steelfiberindia.in/duraflex-steel-fiber-3/>)

A great advantage of fibre's dispersion through the concrete matrix is that the reinforcement reaches also corners and cover areas. As a result, the impact and fatigue resistance is increased and the chipping and spalling behaviour reduced.

Durability

In terms of durability, fibre reinforced concrete is less susceptible to corrosion. As the fibres are short and form a discontinuous media, they rarely touch each other. As a result, no conductive path for stray or induced currents from electromotive potential between different areas occurs. Therefore, the corrosion potential is significantly reduced (Singh 2017).

Steel and polypropylene fibres are the most common fibres used in concrete mixes. Both types of fibres contribute to the improvement of concrete in fire and at elevated temperatures conditions.

Polypropylene fibres tend to minimize spalling in concrete under fire conditions. This kind of fibres melt at relatively low temperatures around 170°C and therefore channels inside the concrete are created. These channels let the steam pressure in concrete escape which prevents the small explosions that cause the spalling of the concrete (Hurley et al. 2015).

Steel fibre reinforced concrete present at elevated temperatures more beneficial mechanical properties against fire conditions. In the following two graphs (See Figure 5.4), the effect of temperature in the compressive and tensile strength of the concrete are shown.

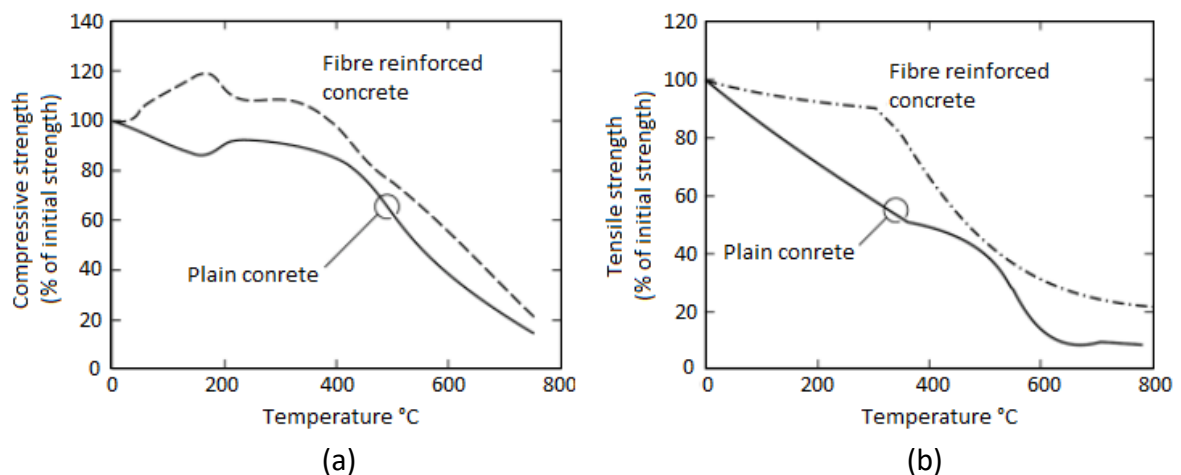


Figure 5.4 Effect of temperature on compressive strength of SFRC (a). Effect of temperature on tensile strength of SFRC (b). (Hurley et al. 2015)

As can be seen in Figure 5.4(a), the compressive strength in SFRC tends to increase between the temperature range of 0-200°C. However, from 400°C both in plain concrete and in SFRC the compressive strength decreases considerably. As can be seen in Figure 5.4(b), the tensile strength of SFRC decreases at a lower rate than that of plain concrete with temperature and it never exceeds the initial tensile strength. The advantage of SFRC is that with the increase of tensile strength, the propagation of cracks is delayed (Hurley et al. 2015).

The increase of impact and fatigue resistance is also related to the increase of ductility in the behaviour of the FRC. The fibres allow the redistribution of stresses easily after impacts.

Cost savings

In every civil construction, the costs are a very important parameter that must be considered. Therefore, the advantages in terms of cost savings of FRC in comparison with conventional reinforced concrete are presented below. However, the costs vary considerably depending on the type and location of the construction site, it is important to mention the advantages of fibres.

One key aspect is the reduction of the amount of steel. Conventional rebar requires bigger amounts of steel in comparison to the fibres. Even though the price of the fibres is higher, the amount required is smaller. Therefore, in some cases the use of FRC can be more cost-effective.



Figure 5.5 Tunnel segment reinforcement construction (a). Reinforcement storage area (b)
 (http://www.tunnel-online.info/en/artikel/tunnel_2011-01_Steel-fibre-reinforced_segmental_linings_State-of-the-art_and_completed_1076896.html)
 (<https://www.tunneltalk.com/Mexico-City-Emisor-Oriente-30May13-Mega-drainage-project-site-visit-report.php>)

One important aspect that must be also considered is the storage area that the reinforcement requires. Conventional reinforcement requires a bigger storage area in comparison to fibres what results in higher costs. (see Figure 5.5(a) and (b)). The use of FRC simplifies the construction process and accelerates the speed of execution what results in shorter times. Furthermore, the number of working operators is smaller.

It is important to underline, that the introduction of structural fibres in the manufacturing of concrete members is still not so common. Therefore, depending on the location of the construction site, fibres may not be available and their import could significantly increase the costs.

5.2 MECHANICAL PROPERTIES OF SFRC

Concrete is a brittle material and has a low tensile strain capacity. However, the development of tensile stresses in concrete members occurs as a result of multi-axial states of stress caused by external loading. Therefore, it is mandatory to increase the tensile stress resistance of the concrete with any kind of reinforcement to obtain a satisfactory performance both under compression and tension stresses.

As concrete is a composite material, it presents a weaker zone in the separation of the constituent materials mainly around the coarse aggregates at their interface with the hydrated cement matrix. The weaker zone is called interfacial transition zone. As a result of tensile stresses, the microcracks in the interfacial transition zone propagate rapidly. Once the strain overcomes the limiting tensile strain capacity of the concrete, it cracks abruptly and with a brittle nature.

In the case of SFRC, which is the most widely used for structural purposes, the value of its cracking tensile strength can be assimilated to the one of plain concrete as the contribution of the fibres starts only after the concrete cracks. The difference between plain concrete and SFRC is that the SFRC presents a significant residual strength f_R because of the fibres after cracking.

The fibres contribute in a positive way in the concrete performance after cracking by providing a bridging effect between the crack surfaces. This is possible as they are randomly distributed in the concrete member and oriented in almost every possible direction. The efficiency of the fibres in the crack bridging is greatly influenced by the amount of fibres crossing the crack, their pull-out behaviour and their strength properties. Their pull-out behaviour of the fibres in the concrete matrix depends on its adhesion, friction and mechanical anchorage.

To characterize the behaviour of the SFRC, the stress-crack opening $[\sigma-w]$ relationship and consequently the stress-strain response $[\sigma-\epsilon]$ are generated. The $[\sigma-w]$ basically describes the stresses (σ) carried by the steel fibres across a crack as a function of the crack-width "w". This procedure was first introduced by Hillerborg et al. (1976). The geometrical parameters of the fibre ($l/d, V_f$) and the volume fraction play a significant role to the shape of the $[\sigma-w]$ curve.

In Figure 5.6, the stress-strain behaviour of the FRC due to tensile stresses is shown. As can be seen, the behaviour of the FRC can be considered as the combination of the effect of the concrete matrix, the fibres and the loss of adhesion. In the first stages before cracking, the FRC behaves like mass concrete. However, it is not until cracks occur that the fibres start to work. After some time, fibres start to lose the adhesion to the concrete matrix and therefore, the stresses are reduced.

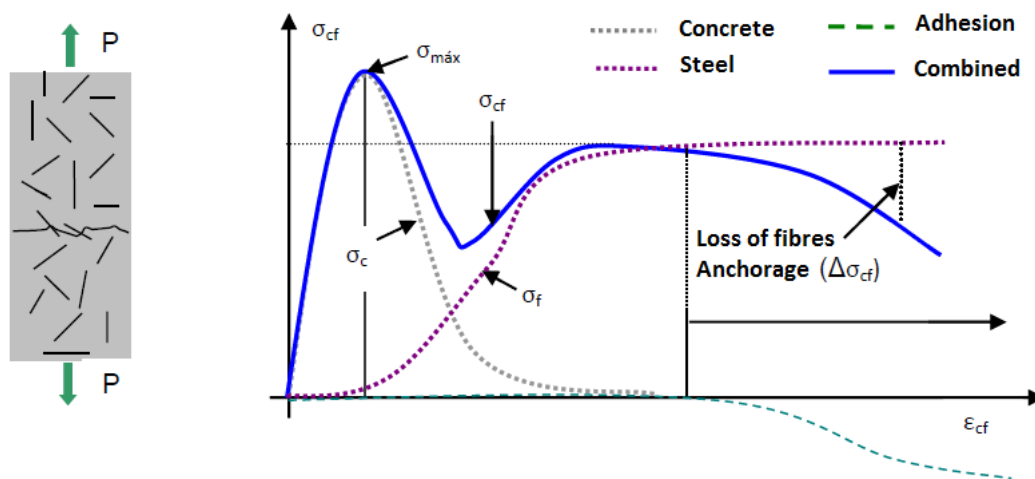
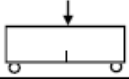





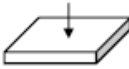



Figure 5.6 Tensile stress behaviour of FRC. (Aguado and Blanco 2015)

As mentioned above, when fibres have a structural function, the values of the residual characteristic tensile strength due to bending, $f_{R,1,k}$ and $f_{R,3,k}$ shall be calculated in order to design the FRC members. Most European codes use bending tests to characterize the post-cracking behaviour of the FRC and to determine the parameters for their constitutive models. In Table 5.2 the main test methods to characterize the post-cracking behaviour of FRC are shown. In the case of EHE-08, the proposed test to determine the load-crack opening diagram $[\sigma-w]$ is the one in UNE-EN 14651. The parameters defining the constitutive model presented in the EHE-08 are the residual flexural strengths obtained from a 3-point bending test (UNE-EN 14651). Nevertheless, other tests like the Barcelona test (UNE 83515 (AENOR 2010)) may be also used.

Table 5.2 Main test methods for the characterization of the post cracking behaviour of FRC. (Blanco, 2013)

Test	Standard / Reference	Setup	Dimensions ¹ [mm]
3-point bending test	EN 14651:2005		600 x 150 x 150
4-point bending test	NBN B 15-238		600 x 150 x 150
Uniaxial tensile test	RILEM TC 162-TDF recommendations		$\phi 150 \times 150$
Wedge-splitting test	Tschegg and Linsbauer (1986)		150 x 150 x 150
Barcelona test	UNE 83515:2010		$\phi 150 \times 150$
Double-edge wedge splitting test	di Prisco <i>et al.</i> (2010)		150 x 150 x 150
EFNARC panel test	EFNARC European Specification for Sprayed Concrete		600 x 600 x 10
Round panel test	ASTM C1550 - 10a		$\phi 800 \times 75$

From the proposed test (UNE-EN 14651), the load-crack opening diagram is generated (See Figure 5.7). Using the values corresponding to the limit of proportionality F_L and the values of the stress F_1 and F_3 corresponding to crack openings of 0,5 mm and 2,5 mm respectively, the corresponding Flexural tensile strength value $f_{ct,fl}$, and the values of the residual flexural strength $f_{R,1}$ and $f_{R,3}$ can be determined. The values of the $f_{ct,fl}$, $f_{R,1}$ and $f_{R,3}$ are calculated by assuming a linear elastic distribution of stresses at the fracture point (EHE-08 2008).

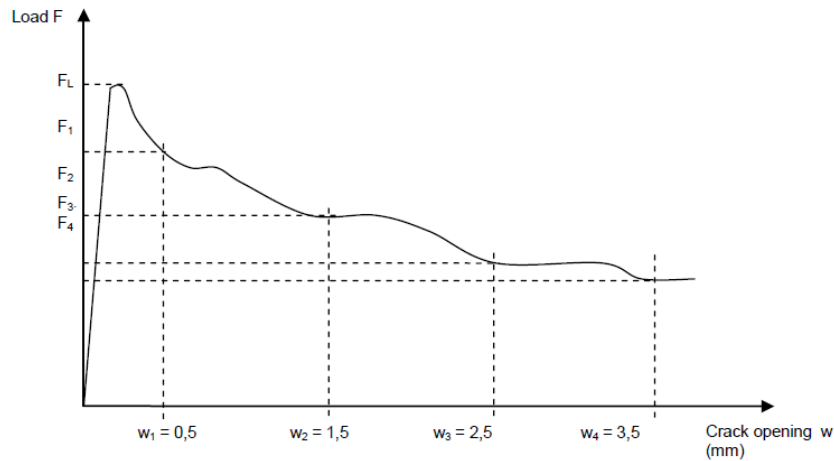


Figure 5.7 Typical load-crack opening diagram. (EHE-08 2008)

5.2.1 Influence of the orientation of the fibres

Another important parameter that has a great influence in the behaviour of the SFRC is the orientation of the steel fibres in the member. In case that the fibres get aligned along the tensile stress trajectories in the member, the transferring of the stresses across the cracked surfaces is more effective.

The orientation of the fibres in the concrete matrix is influenced by the production conditions of FRC. According to Blanco (2013), the preferential orientations of the fibres in the concrete matrix are due to several factors: the fresh-state properties, the concrete pouring, the geometry of the formwork, the type of vibration and the production method.

According to literature (Romualdi and Mandel 1964; Stroeven 1979; Soroushian and Lee 1990; Akkaya et al. 2000; Gettu et al. 2005; Dupont and Vandewalle 2005; Stähli et al. 2008), the fibres tend to align themselves parallel to the external surface of the mould, what is reported as wall-effect. A study carried by Martinie and Roussel (2011), identifies two main reasons for the wall-effects: the geometry of the formwork-mould and the flow of concrete, which depends on the rheological properties of the material, the geometry of the formwork and the casting procedure. In Figure 5.8 the wall-effect with different boundary conditions is shown.

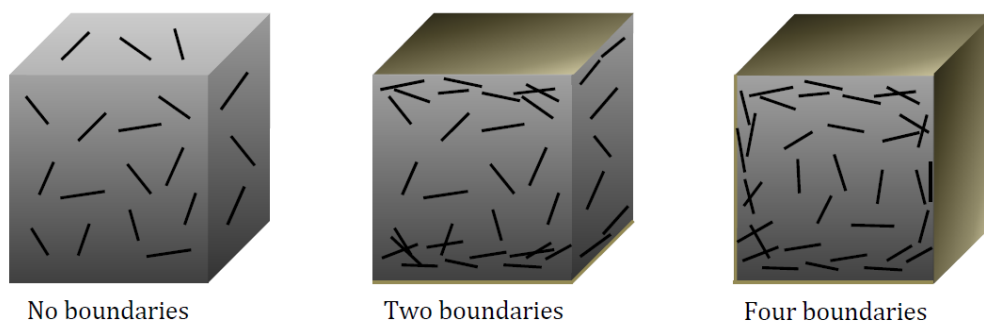



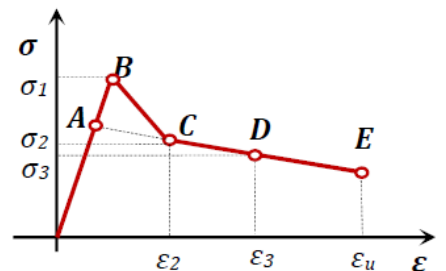
Figure 5.8 Wall-effect with different boundary conditions. (Blanco 2013)

5.3 CONSTITUTIVE MODELS FOR THE DESIGN OF SFRC MEMBERS ACCORDING TO THE EHE-08

There are several European codes and guidelines for the design of FRC structures. However, only the recommendations of the Annex 14 of the Spanish regulation EHE-08 are considered in this chapter. The Spanish regulation EHE-08, proposes two $[\sigma-\varepsilon]$ diagrams: a rectangular diagram and a multilinear diagram (See Table 5.3). The parameters that define these diagrams are the ones obtained in the test mentioned before (UNE-EN 14651).

For the design of FRC members in ULS or SLS, the design values of the residual flexural strengths due to bending ($f_{R,1,d}$ and $f_{R,3,d}$) are calculated by dividing them into a safety factor γ_c . The safety factor usually considered is the same as the one for the concrete ($\gamma_c = 1,5$).

Table 5.3 Constitutive models considered in EHE-08. (Blanco et al. 2013)

Diagram	Parameters
 <p>The diagram shows a horizontal line at stress level σ_1 extending to a strain ε_1 on the x-axis. The y-axis is labeled σ and the x-axis is labeled ε.</p>	$\sigma_1 = f_{ctRd} = 0.33 f_{R,3,d}$ $\varepsilon_1 = \varepsilon_u = [20\text{‰ bending; } 10\text{‰ tensile}]$
 <p>The diagram shows a piecewise linear curve starting from the origin. Points A, B, C, D, and E are marked on the curve. The corresponding strain values on the x-axis are ε_2, ε_3, and ε_u. The y-axis is labeled σ and the x-axis is labeled ε.</p>	$\sigma_1 = f_{ct,d} = 0.6 f_{ct,f,d}$ $\sigma_2 = f_{ctR1,d} = 0.45 f_{R,1,d}$ $\sigma_3 = f_{ctR3,d} = k_1(0.5 f_{R,3,d} - 0.2 f_{R,1,d})$ $\varepsilon_2 = 0.1 + 1000 \cdot f_{ct,d} / E_c$ $\varepsilon_3 = 2.5 / l_{cs} \text{ (} l_{cs} \text{: characteristic length)}$ $\varepsilon_u = [20\text{‰ bending; } 10\text{‰ pure tension}]$

5.4 PRACTICAL CASE

In the previous chapters, some of the main possible damaging stresses developed in a segment during construction stage were identified. Four cases of uneven support of the segments, the effect of the hydraulic jacks' pressure and the effect of the radial eccentricity of the hydraulic jacks were analysed.

In this section, the equations calculated in the previous chapters are used to determine the value of the stresses developed in the tunnel segments. With the real values of the segment's geometry and the pressure of the hydraulic jacks of the Font Santa-Trinitat tunnel of water conduction, a reinforcement based in both conventional rebar and steel fibres is proposed. The possible design of the fibre reinforcement proposed can be calculated by means of the Annex 14 of the Spanish regulation EHE-08. However, in this study only the possible advantages of fibres according to every loading case are exposed.

In the following Table 5.4, the relevant data of the FontSanta-Trinitat tunnel is presented.

Table 5.4 Data of FontSanta-Trinitat tunnel

Year	2010
Type of ring	Universal
Nº segments	5+1 key segment
External diameter (mm)	5700
Internal diameter (mm)	5200
Length of the segment L (mm)	3210
Width of the segment H (mm)	1400
Edge of the segment e (mm)	250
Hydraulic jack's pushing force (KN)	1646

The steel fibres, the rebar and the concrete have the following characteristics:

Table 5.5 Characteristics of the Steel fibres, Steel and Concrete

Steel fibres	
Length (mm)	20
Diameter (mm)	1,0
Tensile strength of the fibres f_{ft} (N/mm²)	1100
Residual tensile strength $f_{ctR3,d}$ (N/mm²)	0,308
Volume fraction V_f (Kg/m³)	40
Rebar B-500-S	
Yield strength f_{yk} (N/mm²)	500
Concrete C50/60	
Compressive strength f_{ck} (N/mm²)	50

The following calculations and the corresponding theoretical design of the reinforcement are done in the Ultimate limit state (ULS) according to the EHE-08.

5.4.1 Uneven supports

In Chapter 3 four cases of uneven supports are analysed. However, only three of them present tensile stresses that can induce to cracking in the segments. As follows, the three relevant cases are presented with the corresponding equations to calculate the tensile stress T_1 . In Table 5.6, the Sketch of each case and the corresponding formula of T_1 are shown.

Table 5.6 Uneven support cases

Cases	Sketch	Formula of T_1
Case 1		$T_{11} = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{L/2} \right) \right)$
Case 3		$T_{13} = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{L/4} \right) \right)$
Case 4		$T_{14} = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{L/4} \right) \right)$

In case 1, the worst scenario is when the eccentricity of the longitudinal joint is in the position under the hydraulic jack's shoe. In this case, the main tensile stresses are developed in the upper part of the segment between the point of application of the loads. With the formula presented in the previous chapter developed through the strut-and-tie method, the tensile stress T_1 is calculated.

$$T_{11}(x) = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{\frac{3L}{4} - x} \right) \right) \quad (5.1)$$

Considering that the worst scenario is with a value of the eccentricity $x = L/2$, the formula is as follows:

$$T_{11} = P \cdot \cot \left(\tan^{-1} \left(\frac{H}{L/2} \right) \right) \quad (5.2)$$

In case 3 and 4, the value of the tensile stress T_1 is the same according to the geometry considered in the calculation. Nevertheless, the position of the tensile stress is not the same. In case 3, the main tensile stress occurs in the lower part of the segment in comparison to case 4 that occurs in the upper middle part of the segment.

$$T_{13} = T_{14} \quad (5.3)$$

With the values presented in Table 5.4 the value of the tensile stress T_1 is calculated:

$$T_{11} = 1646 \cdot \cot \left(\tan^{-1} \left(\frac{1400}{3210/2} \right) \right) = 1887,02 \text{ KN} \quad (5.4)$$

$$T_{13} = T_{14} = 1646 \cdot \cot \left(\tan^{-1} \left(\frac{1400}{3210/4} \right) \right) = 943,51 \text{ KN} \quad (5.5)$$

Theoretical design of the segment reinforcement including steel fibres

The segment reinforcement is designed the way that the contribution of the concrete in the tensile strength is not considered.

$$T = \underbrace{\left\{ \Delta_s \cdot f_{yd} \right\}}_{\text{Rebar}} + \underbrace{\left\{ \Delta_c \cdot f_{ctR3,d} \right\}}_{\text{Fibres}} \quad (5.6)$$

$$T_{11} = \Delta_s \cdot f_{yd} + \Delta_c \cdot f_{ctR3,d} = 1887,02 \text{ KN} \quad (5.7)$$

$$T_{13} = T_{14} = \Delta_s \cdot f_{yd} + \Delta_c \cdot f_{ctR3,d} = 943,51 \text{ KN} \quad (5.8)$$

$f_{ctR3,d}$ = residual tensile strength of SFRC

$f_{yd} = \frac{f_{yk}}{\gamma_s}$ yield strength of steel

Δ_s = area of the passive reinforcement

Δ_c = tensioned area of the concrete

γ_s = factor of safety of steel

The types of failure in the three cases mentioned above, are all the possible appearance of cracks due to the high tensile stresses developed in the segment because of the hydraulic jack's pressure. In all three cases, the most effective type of reinforcement is the conventional rebar as it can be placed exactly in the direction of the tensile stresses that must be absorbed. Nevertheless, the introduction of the steel fibres may have a positive influence in the concrete matrix by reducing significantly the crack widths and increasing the ductile behaviour of the member.

5.4.2 Solid block member under concentrated load

In this situation, the effect of the pushing pressure of the hydraulic jack in a transversal cut of the segment is analysed. Chapter 3 presents the equation to calculate the value of the tensile stress T developed under the hydraulic jack's shoe.

In Figure 5.9 the geometry of the transversal cut of the segment and the type of segment failure are shown. The type of failure is a longitudinal crack due to the tensile stresses developed approximately in a distance of $\frac{a_1}{4} + \frac{a}{2}$ from the segment's corner.

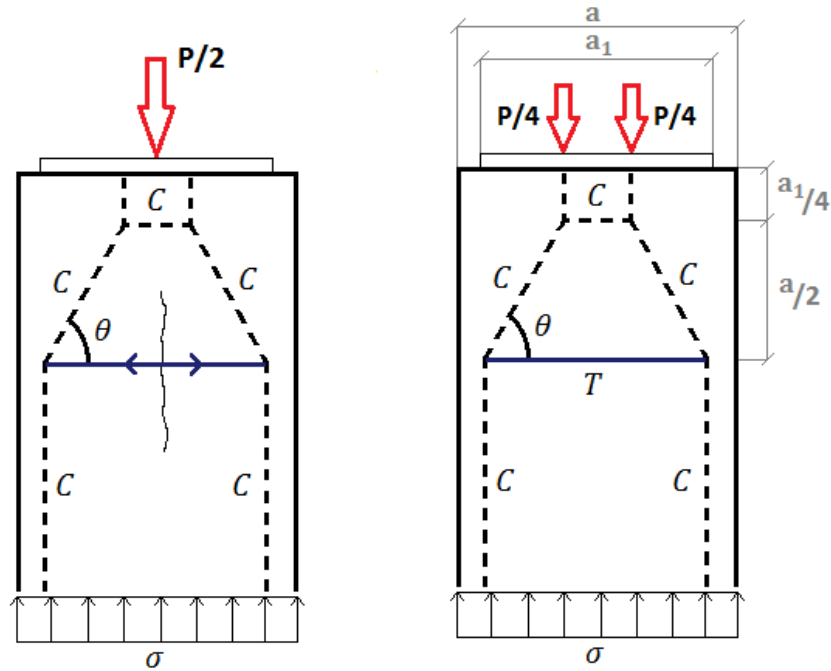


Figure 5.9. Solid block member under concentrated load with a Strut-and-tie model of the stress field.

Equation of the tie T according to EHE-08:

$$T = 0,25 \cdot N_d \cdot \left(\frac{a - a_1}{a} \right) \quad (5.9)$$

$$N_d = P/2 \quad (5.10)$$

In this case, the dimensions of the hydraulic jack's shoe (a_1) and the edge of the segment (a) are required.

$$a = 250 \text{ mm} ; a_1 = 200 \text{ mm}$$

As follows the value of the tensile stress T is calculated:

$$T = 0,25 \cdot N_d \cdot \left(\frac{a - a_1}{a} \right) = 0,25 \cdot \frac{1646}{2} \cdot \left(\frac{250 - 200}{250} \right) = 41,15 \text{ KN} \quad (5.11)$$

Theoretical design of the segment reinforcement including steel fibres

The segment's reinforcement is designed the way that the contribution of the concrete in the tensile strength is not considered.

$$T_1 = \underbrace{\left\{ \Delta_s \cdot f_{yd} \right\}}_{\text{Rebar}} + \underbrace{\left\{ \Delta_c \cdot f_{ctR3,d} \right\}}_{\text{Fibres}} = 41,15 \text{ KN} \quad (5.12)$$

$f_{ctR3,d}$ = residual tensile strength of SFRC

f_{yd} = yield strength of steel

Δ_s = area of the passive reinforcement

Δ_c = tensioned area of the concrete

In this case, the effect of the hydraulic jack's pressure on a transversal cut of the segment is considered. The appearance of tensile stresses under the hydraulic jack's shoe can lead to longitudinal cracks as explained in Chapter 4.

The most effective type of reinforcement is also the conventional rebar, as the rebar can be placed in the direction of the tensile stresses. However, the introduction of fibres may have the same advantages as in the case of the uneven supports, by reducing crack widths and increasing the ductile behaviour of the member.

5.4.3 Radial eccentricity

In this case, compressive stresses are concentrated on the edge of the segment due to the radial eccentricity of the hydraulic jacks. Sometimes in reality can happen that because of durability issues, the rebar cannot reach the edge of the segment. For this reason, in this case the introduction of fibres can be very useful.

In Figure 5.10 the geometry of the fractured piece is shown. If a transversal cut in the fractured piece is done, the shape of it can be assimilated to a triangle of edges a and b and hypotenuse h. To calculate the area of the fractured piece, an approximation with a quadrilateral of edges h and L is done.

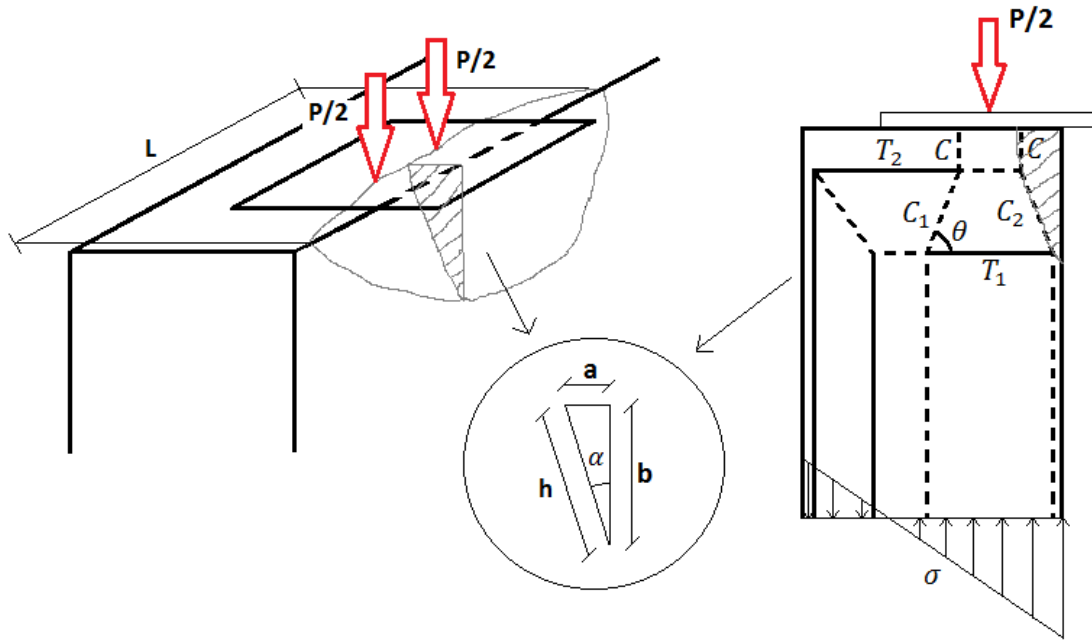


Figure 5.10 Geometry of the segment's fractured piece.

In Chapter 4, the compressive stress C_2 is calculated:

$$C_2 \cong \frac{P}{2} \cdot \frac{1}{\cos \alpha} \cong \frac{1646}{2} \cdot \frac{1}{\cos \frac{\pi}{4}} = 1163,90 \text{ KN} \quad (5.13)$$

Theoretical design of the segment reinforcement including steel fibres

In this case the conventional reinforcement is not considered as the rebar do not reach the edge of the segment. The type of failure is a shear failure.

$$C_2 \cong \underbrace{\left\{ \Delta_c \cdot \tau_c \right\}}_{\text{Concrete}} + \underbrace{\left\{ \Delta_c \cdot f_{ctR3,d} \right\}}_{\text{Fibres}} = 1163,90 \text{ KN} \quad (5.14)$$

As follows the parameters of the previous equation are presented:

$$\tau_c \cong f_{ct} = 0,3 \cdot f_{ck}^{2/3} = \text{shear resistance of concrete} \quad (5.15)$$

$$\Delta_c \cong \text{area of the fractured piece} \cong h \cdot L$$

$$f_{ctR3,d} = \text{residual tensile strength of SFRC}$$

$$\alpha = \text{can be taken as } \frac{\pi}{4}$$

Parameter τ_c corresponds to the shear resistance of the concrete that can be approximated as f_{ct} which is the tensile stress resistance of the concrete. f_{ct} is calculated through the formula exposed in the EHE-08. The value of the residual tensile strength of the SFRC $f_{ctR3,d}$ is calculated according to the constitutive model exposed in the EHE-08. The value of α is for an average concrete the most common value.

In Figure 5.11 the effect of the fibres in the fractured piece is shown. This effect is called bridge effect, as it is explained in Chapter 2 the fibres allow the transmission of stresses and avoid the opening of the crack. In this case they would be able to avoid the fracture.

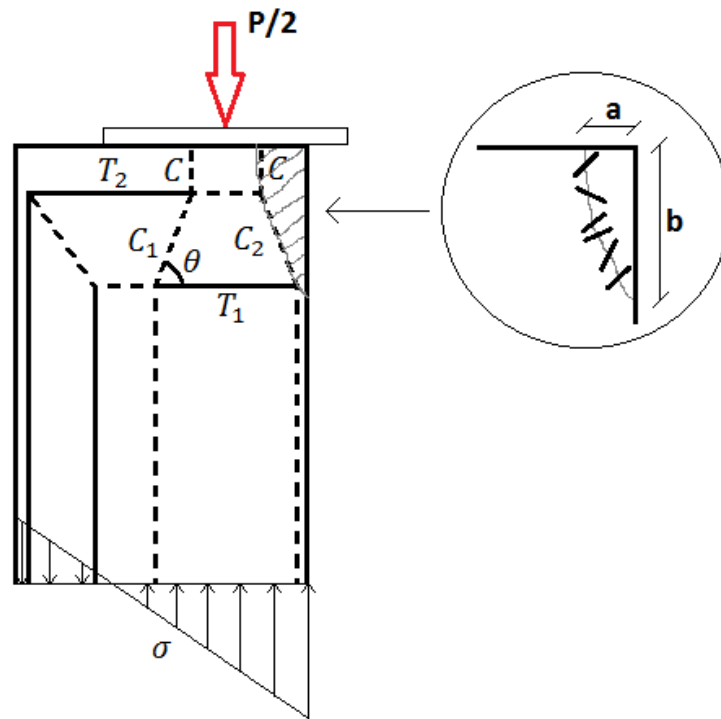


Figure 5.11 Effect of the fibres in the fracture due to high eccentricity of the hydraulic jacks.

In this case, the effect of the radial eccentricity of the hydraulic jacks can lead to a concentration of compressive stresses on the edge of the segment, right under the hydraulic jack's shoe.

As in this case it is considered that the most damaging situation is when the conventional rebar does not reach the edge of the segment, the introduction of fibres with structural purposes may be a very useful solution to resist the stresses developed. The fibres are able to resist the shear stresses in the fracture by producing a bridging effect between the concrete pieces (see Figure 5.11).

6. CONCLUSIONS

6.1 GENERAL CONCLUSIONS

As previously mentioned, damages in tunnel segments may occur in reality due to several reasons. In recent research, it has been proven that the most dangerous stage for the segments is the construction stage. Therefore, in this paper, some of the possible causes of segment damage during this stage have been carefully analysed. The two possible causes analysed are: the uneven support conditions of the segments in the circumferential joints and the radial eccentricity of the load applied by the hydraulic jacks.

In the study of the uneven supports, four possible cases of uneven support conditions are identified (see Table 3.1). Nevertheless, the case where the highest tensile stresses are developed is in case number 1. The worst scenario in this case is when the support in the circumferential joint presents a high eccentricity. It is considered in the analysis that the maximum eccentricity possible is when the support is under the point of force application. The type of structural failure that may occur is longitudinal cracks in the tensioned area of the segment.

Apart from the structural failure that may take place in the segments due to the high tensile stresses, a punctual failure in some parts of the segment's edges and corners may occur. The punctual failure is likely to occur in all the cases mentioned in Chapter 3. The interaction between segments is highly influenced by the support conditions when the pushing force is

applied. These uneven supports may induce reduced contact areas between the segments, what may result in high stress concentrations in these areas. As can be seen in the figures of the segment's damage for every case, these areas are usually the corners of the segments. As a result of the reduced areas of force transmission between segments, the corners may break.

In chapter 4, the effect of radial eccentricity in the damage of the segments have been studied. However, first of all, the loading case of the segment without eccentricity has been analysed in order to understand better the behaviour of the stresses in the segment due to the application of a concentrated load. It can be concluded that the kind of failure in the segment due to the pushing pressure can be assimilated to the one in a compression test or in an indirect tensile stress test. In both tests, tensile stresses are developed in the middle part of the specimen and as a result longitudinal cracks occur. Nevertheless, if the eccentricity reaches a certain value, the triaxial compressive stress field formed under the shoe of the jack moves very close to the edge of the segment. As a result, a shear failure may occur. The type of failure can be assimilated to the one in the upper and lower part of a specimen tested in an indirect tensile stress test (See Figure 4.6(b)).

The last field of study is the use of FRC in the precast concrete tunnel segments. The fibres can contribute to the improvement of the behaviour of the lining both in structural and durability aspects. For structural aspects, the most widely used type of fibres are the steel fibres and their contribution may be taken into account in the design.

The theoretical design of the reinforcement in chapter 5 have been done according to the Annex 14 of the Spanish regulation. The design proposed in the Annex 14 is very conservative, what results in a little contribution of the fibres. Therefore, the total substitution of the conventional reinforcement for steel fibres according to the loading cases exposed in the chapter of uneven supports and radial eccentricity is not possible. However, the introduction of the fibres in the concrete matrix can be very useful in terms of the punctual failures exposed in chapter 4 and 5. Fibres can provide the segment with reinforcement in the areas where the rebar is not able to reach like in the edges and corners of the segment.

6.2 SPECIFIC CONCLUSIONS

In chapter 1 three areas of study are proposed: the uneven supports of the segments, the radial eccentricity of the hydraulic jacks and the introduction of steel fibres with a structural purpose to the segments. For every area of study, specific objectives are stated and in response to them, the following conclusions are drawn.

Uneven supports of the segments

In chapter 3 the main cases of uneven supports of the segments are identified. Each case is different and presents its own stress field and possible damages. The main concluding remarks for every case are exposed below.

Case 1 Vertical displacement of the support segment

- The highest stress field developed in the segment is the one in the upper middle part of the segment. Due to the pressure of the hydraulic jacks, high tensile stresses occur. In this case, it has been considered how the tensile stress varies with the eccentricity of

the middle support of the segment. As a result, an equation for the tensile stress depending on the eccentricity of the support was obtained.

- With the geometric characteristics of the segments from 6 different tunnels, the value of the tensile stress has been calculated and compared between each other. It can be concluded that the tensile stress increases with the eccentricity of the joint.
- According to Figure 3.11, the value of the tensile stress that depends on the eccentricity grows faster in smaller tunnels.
- In general, the tensile stresses are lower in tunnels with smaller diameters and higher in tunnels with bigger diameters. However, in case of the M30 tunnel in Madrid, even though the tunnel has a big diameter, the tensile stresses are smaller in comparison to other tunnels with similar diameters. This may happen as the overall size of the segment is smaller.
- The value of the tensile stresses grows faster with the eccentricity of the joint in tunnels where the segments have smaller segment's widths "H" (See Figure 3.12).
- It may be concluded according to Figure 3.13 and Figure 3.14 respectively that there are higher tensions in segments with bigger length "L" and in segments with higher " L/H " ratio.
- Two types of failure have been identified in this case of uneven support. The first one is the possible longitudinal cracks developed in the upper middle part of the segment where the high tensile stresses occur. With the increase of the joint's eccentricity, the possibility of failure is higher. The second one is related to the contact between the two segments "i" and "j+1". If the pressure due to the hydraulic jacks is too high, the corner of the segment "j+1" may break.

Case 2 Positive turn of the support segment and negative turn of the analysed segment

- In this case, the main stress field corresponds to a compression strut that goes from one side of the segment to the other. As the worst scenario in this case is when there is no contact with the adjoining ring (ideal situation), the force transmitted by the hydraulic jacks, may only be transferred by the lateral supports with the adjoining segments. Therefore, the most critical points in the segment are the supports in the lateral joints.
- The loading situation of the lateral supports may lead to a punctual failure of the segment's corners. The punctual failure is the break of a piece of segment (segment's corners) and it is triangularly shaped as can be seen in Figure 3.18. The shape of it depends on the direction of the force.

Case 3 Rotation of segments "j" and "j+1"

- Due to the support conditions of the segment, the case can be assimilated to a beam tested in a flexion test where a bending moment occurs.

- In this case the higher tensile stresses identified are in the lower part of the segment. These tensile stresses may lead to longitudinal cracks and due to the bending moment, the segment may fail like a tested beam in a flexion test.
- Through the strut-and-tie method, an equation for the tensile stress developed in the segment is proposed. With the same geometric characteristics of the 6 tunnels analysed in case 1, it can be concluded that the higher the relation " L/H ", the higher the values of the tensile stresses.

Case 4 Rotation of segments "j" and "j+1" (Other direction)

- In this case it was reasonable to consider the eccentricity of the longitudinal joint in the adjoining ring, as the main stress fields may vary with it.
- The first situation considered is with the longitudinal joint of the adjoining ring placed in the middle of the analysed segment. The higher tensile stresses in this situation are developed in the upper middle part of the segment. This situation may lead to longitudinal cracks in the segment in the tensioned area of the concrete.
- The second situation is with the longitudinal joint of the adjoining ring placed right under the hydraulic jacks. In this case, the main stress field is different and correspond to a compression strut that goes from one side of the segment to the other as shown in Figure 3.23(b). As concrete works well under compression, the punctual failure may occur in the contacts between the segments namely, the lateral supports. The edges may break forming a triangularly shape piece of concrete.

Radial eccentricity of the hydraulic jack

- The pressure applied by the hydraulic jacks creates a stress field in the segment. Without any eccentricity, the stress field can be assimilated to the one of a solid block member under a concentrated load.
- In the case of a solid block member under a concentrated load, the type of failure can be assimilated to the one in a compression test or in an indirect tensile stress test. The stress field consists of a state of triaxial compression right under the point of application of the load and tensile stresses in the middle part of the member.
- The failures in a solid block member under a concentrated load are longitudinal cracks placed where the tensile stresses are higher namely, in the middle part of the member.
- If the hydraulic jacks, due to different reasons, apply the force with a certain eccentricity higher than the one established in the design, the stresses are highly concentrated on the edge of the segment. A triaxial compression stress field is formed under the bearing pads and therefore failure may occur.
- The type of failure in the case of excessive radial eccentricity can be assimilated to a shear failure. The way of breaking of the segment's edge can be assimilated to the failure in an indirect tensile stress test specimen as seen in Figure 4.9.

Introduction of fibres in the design of tunnel segments' reinforcement

- Fibres have a good contribution to the segments' reinforcement. They may contribute to the three key aspects: structural, durability and costs.
- The main aspects of the structural contribution can be summarised as follows: increase of crack control and bearing capacity, increase of toughness and ductility and reduction of the crack widths.
- The main durability aspects that are improved by the introduction of fibres are: better performance in elevated temperatures, increase of impact and fatigue resistance and less corrosion and abrasion.
- It is not that clear if the introduction of fibres is a cost-reducing factor. However, it has some advantages such as the reduction of amount of steel, smaller storage areas, less working operators and shorter times. In some cases, other aspects such as the location of the construction site could play a more significant role to the costs.
- The design recommendations for FRC members exposed in the Annex 14 of the Spanish regulation EHE-08 are quite conservative as the contribution of the structural fibres tends to be quite low. As a result, the total substitution of the conventional reinforcement for structural fibres is often not possible according to the EHE-08.
- In the three uneven support cases where the main stresses are high tensile stresses, the most effective type of reinforcement is the conventional rebar as it can be placed exactly in the direction of the tensile stresses that need to be absorbed. Nevertheless, the introduction of the steel fibres may have a positive influence in the concrete matrix by reducing significantly the crack widths and increasing the ductile behaviour of the member.
- The case where the fibres have a more direct contribution is the case of an excessive radial eccentricity. If the eccentricity is too big, the conventional rebar does not reach the edge of the segment. This means that the fibres, as they are spread all over the segment, can act as a bridge and enhance the resistance.

6.3 FUTURE PERSPECTIVES

The quality loss of the tunnel lining during the construction phase is one of the main concerns of the construction companies. Therefore, several investigation lines try to optimize as much as possible the aspects of this stage.

In the present study, the effect of the uneven support conditions of the segments have been analysed. However, some assumptions have been done to do so. One of the assumptions is that the longitudinal joints of the rings are straight. Nevertheless, in reality, there is a recent trend to use oblique joints as they can bring several advantages such as better confinement. It would be interesting to study in a more accurate way the contribution of such joints.

Another assumption that has been considered in the study is that there are only two hydraulic jacks per segment. However, in the recent years, the tendency is to use three. At first sight, the main advantage is that the stresses developed due to the pushing pressure may be

better distributed to the segment as the overall pushing force can be divided into three. It would be interesting to study, in which cases the use of three hydraulic jacks per segment is more optimal depending on the size of the tunnel or the size of the segments.

It is proven that the introduction of fibres with structural purposes in the concrete elements can be very advantageous in many aspects. There are several investigation lines trying to define more accurate constitutive models for the design of FRC elements. However, there is still a lack of design regulations. The appearance of new design regulations would enable the expansion of its usage.

REFERENCES

- American Concrete Institute (2014). ETR Report, Design and Construction of Steel Fiber-Reinforced Precast Concrete Tunnel Segments. (*ACI Committee 544*), Farmington Hills, Michigan, USA.
- Akkaya, Y., Picka, J., & Shah, S. P. (2000). Spatial distribution of aligned short fibers in cement composites. *Journal of materials in civil engineering*, 12(3), 272-279.
- Álvarez, A. B. (2013). *Characterization and modelling of SFRC elements* (Doctoral dissertation, Universitat Politècnica de Catalunya).
- American Concrete Institute (2014) Building Code Requirements for Structural Concrete (*ACI 318M-14*) and Commentary (*ACI 318RM-14*), Farmington Hills, Michigan, USA.
- Arnau, O., & Molins, C. (2012). Three dimensional structural response of segmental tunnel linings. *Engineering Structures*, 44, 210-221.
- Arnau, O., & Molins, C. (2011). Experimental and analytical study of the structural response of segmental tunnel linings based on an in situ loading test. Part 2: Numerical simulation. *Tunnelling and Underground Space Technology*, 26(6), 778-788.
- Bakhshi, M., Nasri, V. (2014a). Review of international practice on critical aspects of segmental tunnel lining Design. In *Proceedings of the 2014 North American Tunneling (NAT) Conference*. Los Angeles, CA. June 22-25, 2014.

- Blom, C. B. M. (2002). *Design philosophy of concrete linings for tunnels in soft soils*. (Doctoral dissertation, TU Delft, Delft University of Technology).
- Buratti, N., Ferracuti, B., & Savoia, M. (2013). Concrete crack reduction in tunnel linings by steel fibre-reinforced concretes. *Construction and Building Materials*, 44, 249-259.
- Burgers, R., Walraven, J., Plizzari, G. A., & Tiberti, G. (2007, May). Structural behavior of SFRC tunnel segments during TBM operations. In *World Tunnel Congress ITA-AITES* (pp. 1461-1467).
- Caratelli, A., Meda, A., Rinaldi, Z., & Romualdi, P. (2011). Structural behaviour of precast tunnel segments in fiber reinforced concrete. *Tunnelling and Underground Space Technology*, 26(2), 284-291.
- Carmona, S., & Aguado, A. (2012). New model for the indirect determination of the tensile stress-strain curve of concrete by means of the Brazilian test. *Materials and structures*, 45(10), 1473-1485.
- Cavalaro, S. H. P. (2009). *Aspectos tecnológicos de túneles construidos con tuneladora y dovelas prefabricadas de hormigón* (Doctoral dissertation, Universitat Politècnica de Catalunya).
- Dupont, D., & Vandewalle, L. (2005). Distribution of steel fibres in rectangular sections. *Cement and Concrete Composites*, 27(3), 391-398.
- Instrucción de Hormigón Estructural (2008). *Chapter 12. Structural Members*. (EHE-08) Madrid: Ministerio de Fomento, Secretaría General Técnica.
- Instrucción de Hormigón Estructural (2008). *Annex 14. Recommendations for using concrete with fibres*. (EHE-08) Madrid: Ministerio de Fomento, Secretaría General Técnica.
- Gettu, R., Gardner, D. R., Saldivar, H., & Barragán, B. E. (2005). Study of the distribution and orientation of fibers in SFRC specimens. *Materials and Structures*, 38(1), 31-37.
- Hillerborg, A., Modéer, M., & Petersson, P. E. (1976). Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. *Cement and concrete research*, 6(6), 773-781.
- Hurley, M. J., Gottuk, D. T., Hall Jr, J. R., Harada, K., Kuligowski, E. D., Puchovsky, M., ... & Wieczorek, C. J. (Eds.). (2015). *SFPE handbook of fire protection engineering*. Springer.
- Japan Society of Civil Engineers (2007), Standard specifications for tunneling-2006: Shield tunnels. *Japan Society of Civil Engineers*.
- Kasper, T., Edvardsen, C., Wittneben, G., & Neumann, D. (2008). Lining design for the district heating tunnel in Copenhagen with steel fibre reinforced concrete segments. *Tunnelling and Underground Space Technology*, 23(5), 574-587.
- Kooiman, A. G. (2000). *Modelling steel fibre reinforced concrete for structural design*. (Doctoral dissertation, TU Delft, Delft University of Technology).
- Leonhardt, F. (1964). *Prestressed concrete: Design and construction*. W. Ernst.
- Analysis of the damage in precast concrete tunnel segments during construction phase and the influence of FRC*

- Martinie, L., & Roussel, N. (2011). Simple tools for fiber orientation prediction in industrial practice. *Cement and Concrete research*, 41(10), 993-1000.
- Meng, G., Gao, B., Zhou, J., Cao, G., & Zhang, Q. (2016). Experimental investigation of the mechanical behavior of the steel fiber reinforced concrete tunnel segment. *Construction and Building Materials*, 126, 98-107.
- Plizzari, G. A., & Tiberti, G. (2006). Steel fibers as reinforcement for precast tunnel segments. *Tunnelling and Underground Space Technology*, 21(3), 438-439.
- Plizzari, G. A., & Tiberti, G. (2007, June). Structural behavior of SFRC tunnel segments. In *Proceedings of the 6th international conference on fracture mechanics of concrete and concrete structures* (Vol. 3, pp. 17-22).
- Romualdi, J. P., & Mandel, J. A. (1964, June). Tensile strength of concrete affected by uniformly distributed and closely spaced short lengths of wire reinforcement. In *Journal Proceedings* (Vol. 61, No. 6, pp. 657-672).
- Singh, H. (2017). *Steel Fiber Reinforced Concrete*. 1st ed. pp.34-35.
- Sorelli, L., & Toutlemonde, F. (2013, May). 5570-On the design of steel fiber reinforced concrete tunnel lining segments. In *ICF11, Italy 2005*.
- Soroushian, P., & Lee, C. D. (1990). Distribution and orientation of fibers in steel fiber reinforced concrete. *Materials Journal*, 87(5), 433-439.
- Stähli P, Sutter M, van Mier JGM (2007) Improving the mechanical properties of HFC by adjusting the filling method. In *Proceedings of RILEM fifth international workshop on high performance fibre reinforced cement composites (HPFRCC5)*. Mainz, Germany, pp 23–30
- Stroeven, P. (1979). Morphometry of fibre reinforced cementitious materials. *Matériaux et Construction*, 12(1), 9-20.
- Sugimoto, M. (2006). Causes of shield segment damages during construction. In *International Symposium on Underground Excavation and Tunnelling*, Bangkok, Thailand (pp. 67-74).
- Thewes, M., & Budach, C. (2009). Grouting of the annular gap in shield tunnelling—An important factor for minimisation of settlements and production performance. In *Proceedings of the ITA-AITES World Tunnel Congress 2009 "Safe Tunnelling for the City and Environment"* (pp. 1-9).

